LP

CR 86210

N69-36999

(ACCESSION NUMBER)

41

(PAGES)

CR-86210

(NASA CR OR TMX OR AD NUMBER)

(THRU)

1

(CODE)

07

(CATEGORY)

FACILITY FORM 602

TEXAS INSTRUMENTS
INCORPORATED

STUDY OF SOLID-STATE INTEGRATED MICROWAVE CIRCUITS—FINAL REPORT

Scientific Report No. 7

U40-811500-40

January 1969

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Electronics Research Center

Cambridge, Massachusetts

Work Performed Under

Contract No. NAS 12-75

Control No. ERC/R&D 65-45

TEXAS INSTRUMENTS

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PREFACE

A study of solid-state integrated circuits under the sponsorship of the Electronics Research Center of the National Aeronautics and Space Administration is being performed by Texas Instruments Incorporated under Contract NAS 12-75. The object of this contract is to design, develop, and test two each of thin-film, hybrid, breadboard telemetry transmitters and receivers.

This report presents the results of work performed under the seventh, eighth, tenth, twelfth, and thirteenth items of the work statement. Items 7 and 8 are concerned with the fabrication and test of two breadboard models of the telemetry transmitter. Items 10, 12, and 13 are concerned with the design, fabrication, and test of the two telemetry receivers.

Separate sections of the report present the transmitter and receiver efforts in detail.

ABSTRACT

This report discusses the final design activity and test results on a microwave FM telemetry receiver and a microwave FM telemetry transmitter.

The transmitter and receiver are presented in separate sections. Circuit analysis and design of individual blocks within the basic units are presented, as well as individual and final test results.

SECTION I

INTRODUCTION

As a result of their proven advantages in size and reliability, integrated circuits have come to be preferred for use in military and space applications. In the next few years, all telemetry links designated for space applications will operate within the 1.7- to 2.3-GHz frequency range. As a result of these trends, a study program was undertaken to establish the feasibility of employing integrated circuit techniques at microwave frequencies.

The first phase was a study of solid-state microwave devices, techniques, and components suitable for use in the 1- to 6-GHz frequency range. In the second phase, basic FM telemetry transmitter configurations suitable for use in the 1- to 6-GHz frequency range and implementation in integrated circuits were investigated. During the third phase, the final transmitter configuration was selected and a detailed design and analysis of the transmitter was completed. Also included in the third phase was a study of computer-aided circuit design techniques and the effects of radiation on integrated circuits. The fourth phase dealt with the development and fabrication of two breadboard transmitters. Also, during the fourth phase a review of microwave devices, techniques, and components was conducted with special consideration given to receiver applications. The fifth phase was a continuation of the transmitter development and fabrication effort. In addition to the transmitter effort, a detailed analysis and design of a PCM/FM receiver intended for use in the 2.2- to 2.3-GHz frequency band was conducted. The sixth phase consisted of the final transmitter fabrication and test, and the final receiver fabrication and test.

This report covers the effort conducted in the sixth and final phase. The feasibility of using integrated circuits in transmitters and receivers for use at microwave frequencies is demonstrated with the fabrication and test of two each telemetry transmitters and receivers.

SECTION II

SUMMARY OF RESULTS

Two FM telemetry transmitters were fabricated and tested. A final transmitter occupies less than 0.75 cubic inch including connectors, and weighs approximately 1.3 ounces. The output power at midband is in excess of 750 mW with a dc-to-RF efficiency greater than 12 percent. The deviation sensitivity is nominally 0.2 volt rms per 100 kHz. Center frequency stability is greater than 0.05 percent without AFC circuitry.

Two FM telemetry receivers were also fabricated and tested. The final receiver occupies less than 1.25 cubic inches and weighs less than 2.5 ounces. The receiver noise figure is nominally 12 dB. With a 6-dB S+N/N, the sensitivity is −81 dBm. The 1.0-dB compression point is greater than −20 dBm.

SECTION III

RECEIVER

A. General

The high-frequency and low-noise performance of semiconductor devices, as well as thin-film techniques and microstrip characteristics, were reviewed in Scientific Report No. 4 (Report No. U26-811500-26). Using the present limitations of these devices and techniques, the feasibility of implementing a telemetry receiver designated to operate within the 2.2- to 2.3-GHz band was investigated and analyzed in Scientific Report No. 6 (Report No. U33-811500-33). The telemetry receiver specifications are shown in Table I. In Scientific Report No. 6 it was shown that a telemetry receiver capable of meeting the specifications in Table I was feasible.

TABLE I. S-BAND TELEMETRY RECEIVER SPECIFICATIONS

Modulation	PCM/FM	Spurious response	50 dB
Operating frequency	2200 to 2300 MHz	Frequency stability	± 0.002 percent
Sensitivity	−110 dBm	Tuning	Semifixed
Bandwidth	2 to 3 MHz minimum	Power input	4 watts, − 24 Vdc
Noise figure	4 to 6 dB	Temperature range	−28°C to 71°C
Dynamic range	50 dB	Size	144 in.^{3}
Image rejection	60 dB	Weight	1 kG

Under the existing contract, three blocks—the preselector filter, the image terminated mixer, and the first stage of the low noise IF amplifier strip—within the overall receiver system are to be built, integrated, and tested. This report will cover the design of these three blocks and their individual tests plus the test results when the three blocks are integrated and functioning as a single unit.

B. Circuit Design and Analysis

1. Mixer

The initial design of the S-band balanced mixer was covered in Scientific Report No. 4; however, results of the noise figure and conversion loss tests performed on the mixer indicated that the original design would not be adequate for good receiver performance and a new mixer design was initiated. The new design is one that recently was analyzed in detail in the literature.[1,2]

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[1] I. Tatsuguchi and E.W. Aslaken, "Integrated 4-GHz Balanced Mixer Assembly," *IEEE Journal of Solid-State Circuits*, Vol. SC-3, No. 1 (March 1968), pp. 23–24.

[2] K.M. Johnson, "X-Band Integrated Circuit Mixer with Reactively Terminated Image," *IEEE Journal of Solid-State Circuits*, Vol. SC-3, No. 2 (June 1968), p. 56.

The branch line hybrid coupler used in the initial mixer design was tested separately and the results of those tests are shown in Figure 1. The test results indicated that the coupler was operating properly and therefore will be used in the mixer redesign.

The mixer diode impedance, as shown in Figure 2, is 75–j25 ohms. Normalized to 50 ohms this corresponds to 1.5–j0.5 ohms. The corresponding shunt admittance is 0.6+j0.2 normalized to 20 millimhos. The resulting shunt admittance is 12+j14 millimhos which corresponds to a shunt impedance of 83.4–j250 ohms. The problem is to match out the reactive portion of the diode impedance with a shunt element. In this case a shorted element will be used so that the short can also be used as a dc return for the diode current. The characteristic impedance Z_0 of the shorted stub was selected to be 72 ohms. The length is determined from the following relationship,

$$Z = jZ_0 \tan B\ell$$

$$250 = j72 \tan B\ell$$

$$B\ell = 74 \text{ degrees}$$

at 2.25 GHz, 74 degrees = 0.473 inch.

As previously shown in Scientific Report No. 6, page 69, equation 136, the optimum source impedance is 72 ohms. The output of the coupler is now transformed from its 50-ohm impedance to the 72-ohm impedance. This is most readily accomplished by using a quarter-wavelength matching section whose characteristic impedance is defined by the following.

$$Z_0 = \sqrt{Z_1 Z_2}$$

where

$$Z_1 = 50 \text{ ohms}$$

$$Z_2 = 72 \text{ ohms}$$

then

$$Z_0 = 60 \text{ ohms.}$$

$$\ell = \lambda/4 \text{ at } 2.25 \text{ GHz} = 0.576 \text{ inch.}$$

To provide an RF ground at the diodes and also to keep the local oscillator signal out of the IF amplifier, a $\lambda/4$ open-circuited stub with a relatively low characteristic impedance Z_0 is used. The low Z_0 is used for two reasons: the open stub will appear as a short at both the local oscillator and signal frequencies, and small errors in length will not have any adverse effects. Z_0 was chosen to be 25 ohms.

To provide image termination, a $\lambda_i/4$ loosely coupled line with a $\lambda_i/4$ open-circuited stub at the end closest to the diode is used where λ_i is the wavelength at the image frequency. This technique will reactively terminate the image in a short circuit. The characteristic impedance of the $\lambda_i/4$ coupled line and the $\lambda_i/4$ stub was chosen to be 60 ohms and the length of each element was calculated to be 0.633 inch.

The mixer was fabricated on 20-mil glazed ceramic and is shown in Figure 3. The test results showing mixer performance are shown in Figure 3.

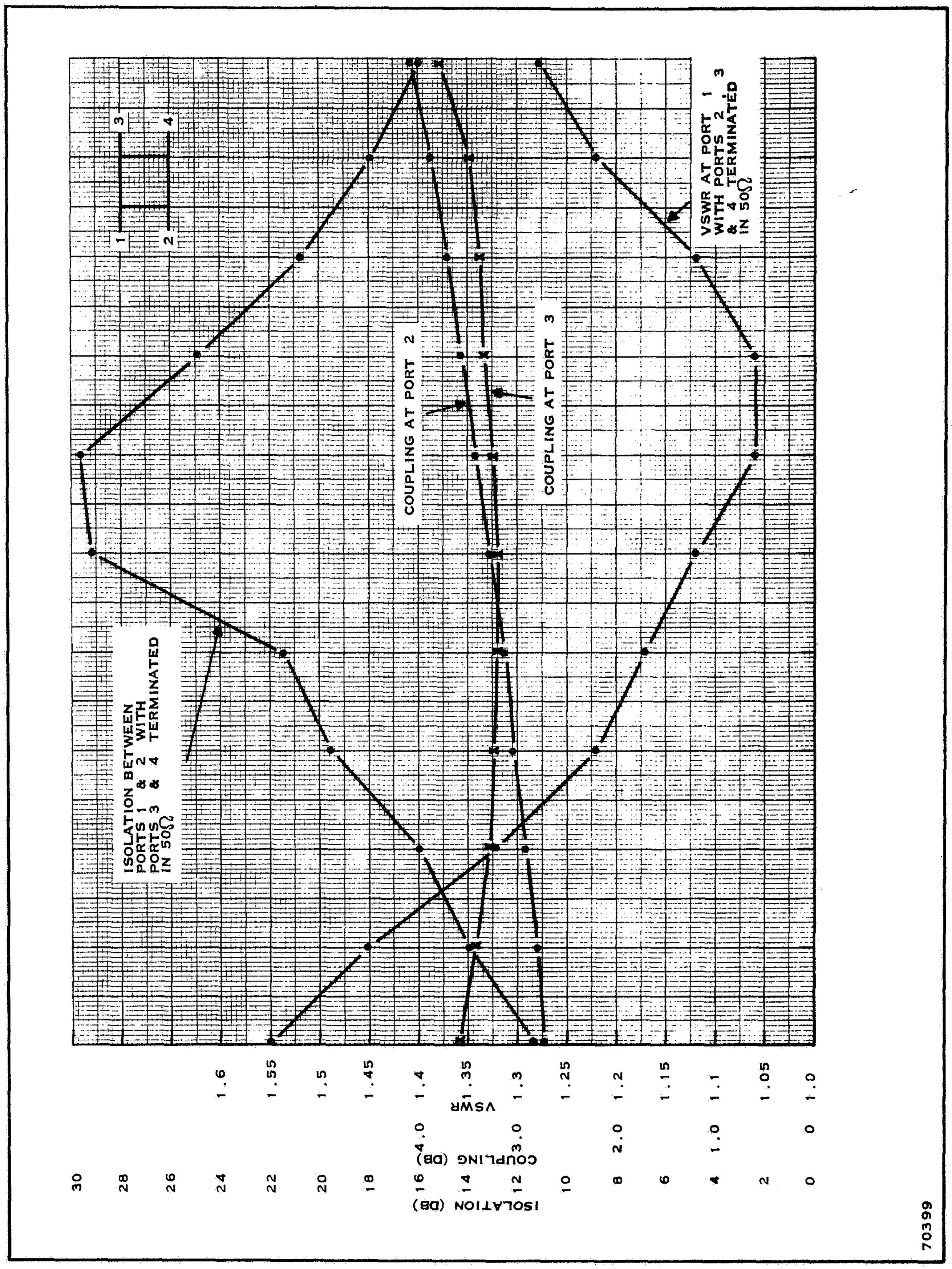

Figure 1. Branch Line Hybrid Coupler Performance

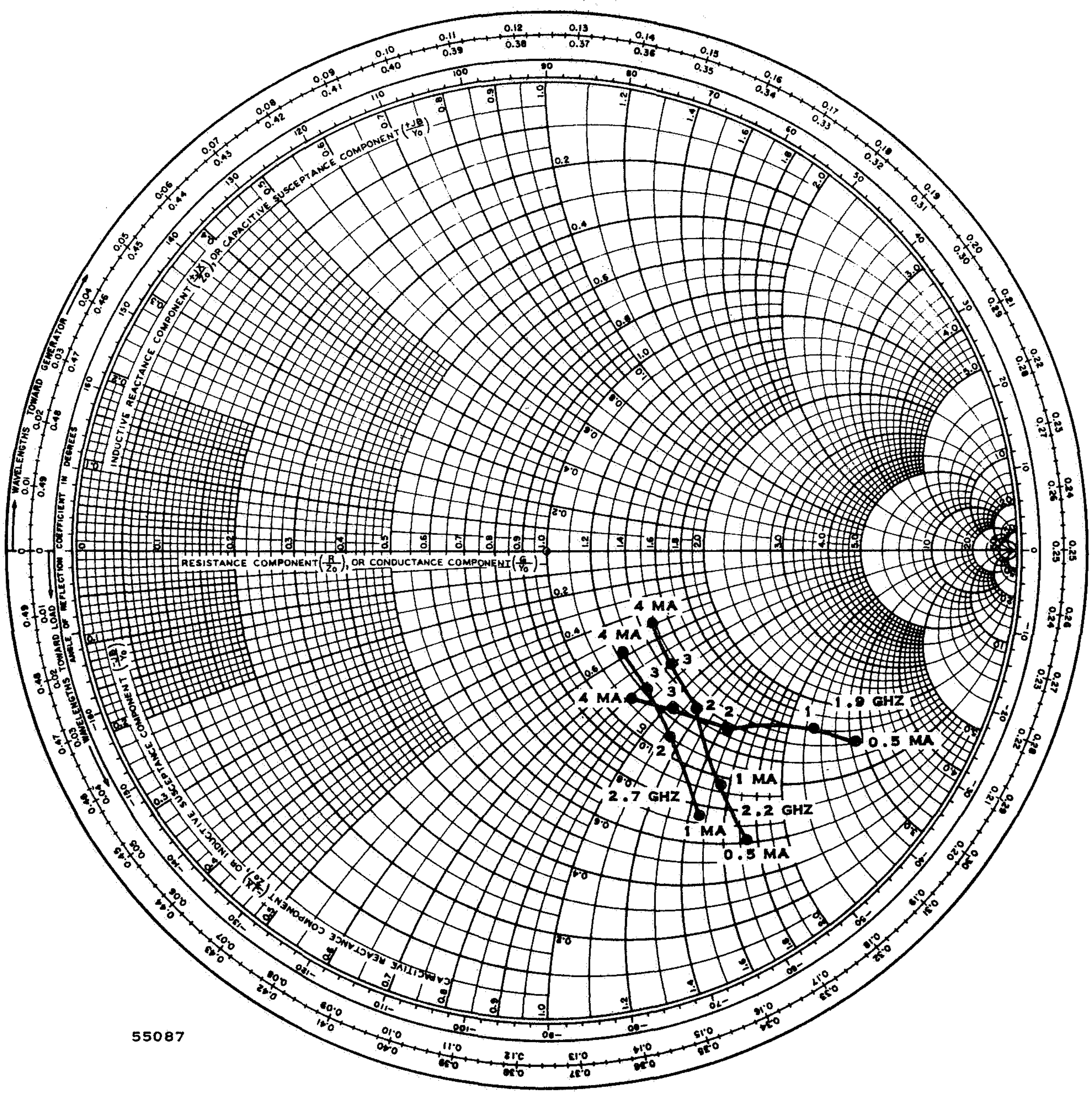

Figure 2. RF Impedance of GaAs Schottky Barrier Diode for Self-Bias

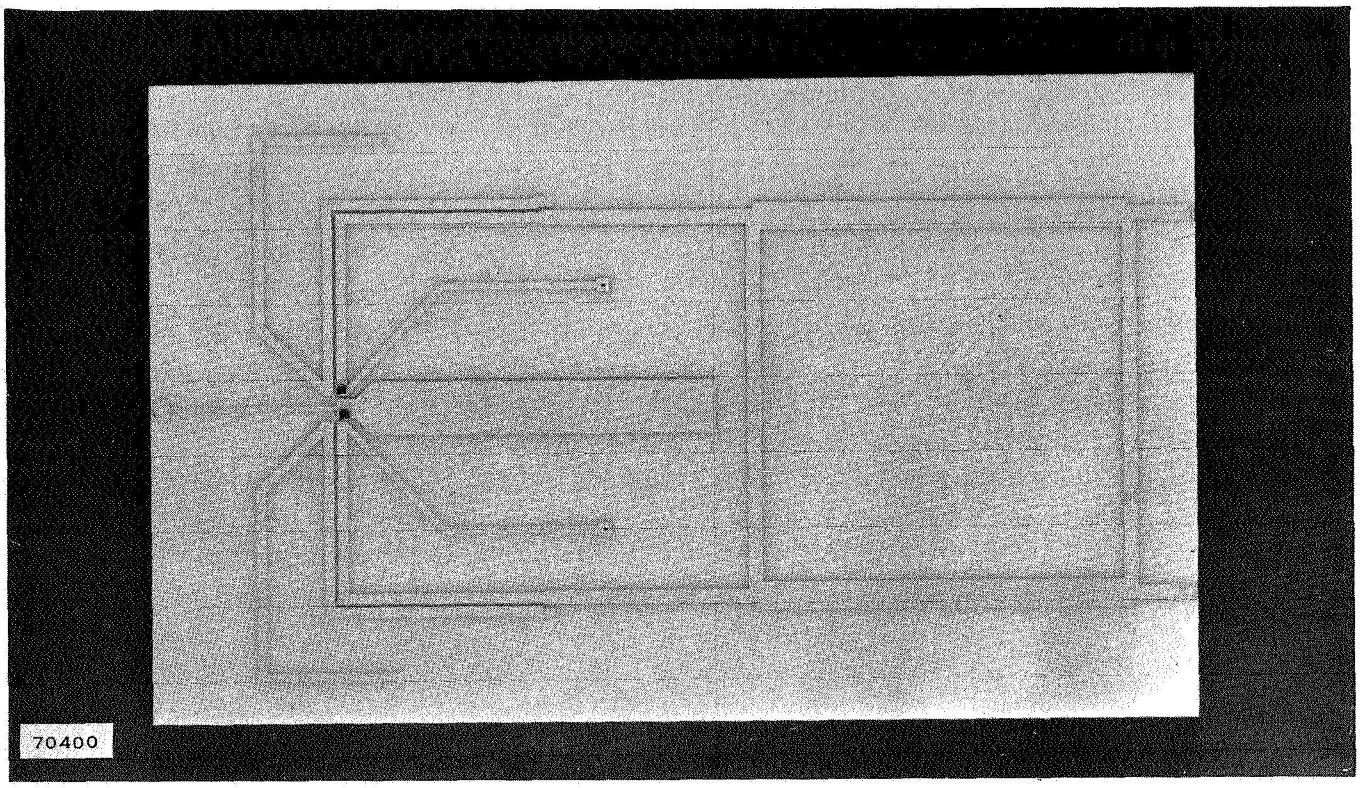

Figure 3. Image Terminated Mixer

From the data shown in Figure 4, it can be seen that the image terminating networks are not centered at 2.05 GHz, the center of the image band. To correct this and center the terminating networks, 15-mil lengths of gold ribbon were added to the ends of the $\lambda_i/4$ coupled line and the $\lambda_i/4$ open stub. Test results after the lengthening of the image terminating networks is shown in Figure 5. In both cases the noise figure measurements were made using a 100-MHz IF amplifier with a 3.5-dB noise figure. The noise figure measurements were made using a Hewlett-Packard Model 342A Noise Figure Meter with Models 343A and 349A Noise Sources. The noise figures shown in Figures 4 and 5 are corrected noise figures using the curve shown in Figure 6.

A second mixer was also built and tested. The noise figures of the mixers are shown in Figure 7.

2. IF Amplifier

The design of the 100-MHz IF amplifier was covered in detail in Scientific Report No. 6. The amplifier was built using conventional components. The construction of the amplifier using conventional components served a twofold purpose: it served as a verification of the paper design, and it could be used in the data measurements performed on the mixer. The conventional component amplifier was built and tested with the following results.

Gain = 15 dB

Noise Figure = 3.5 dB

Bandwidth = 12 MHz

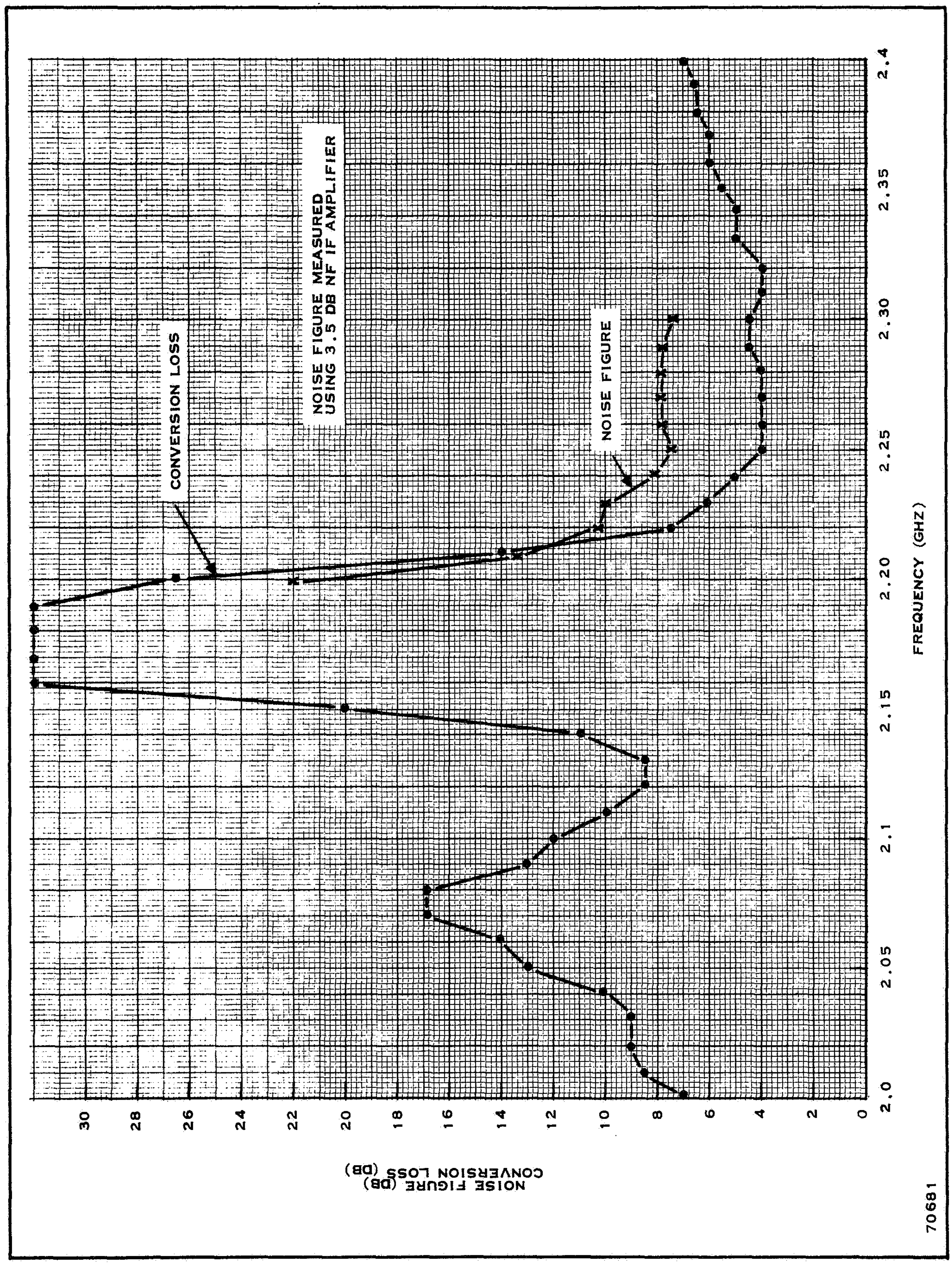

Figure 4. Noise Figure and Conversion Loss Versus Frequency

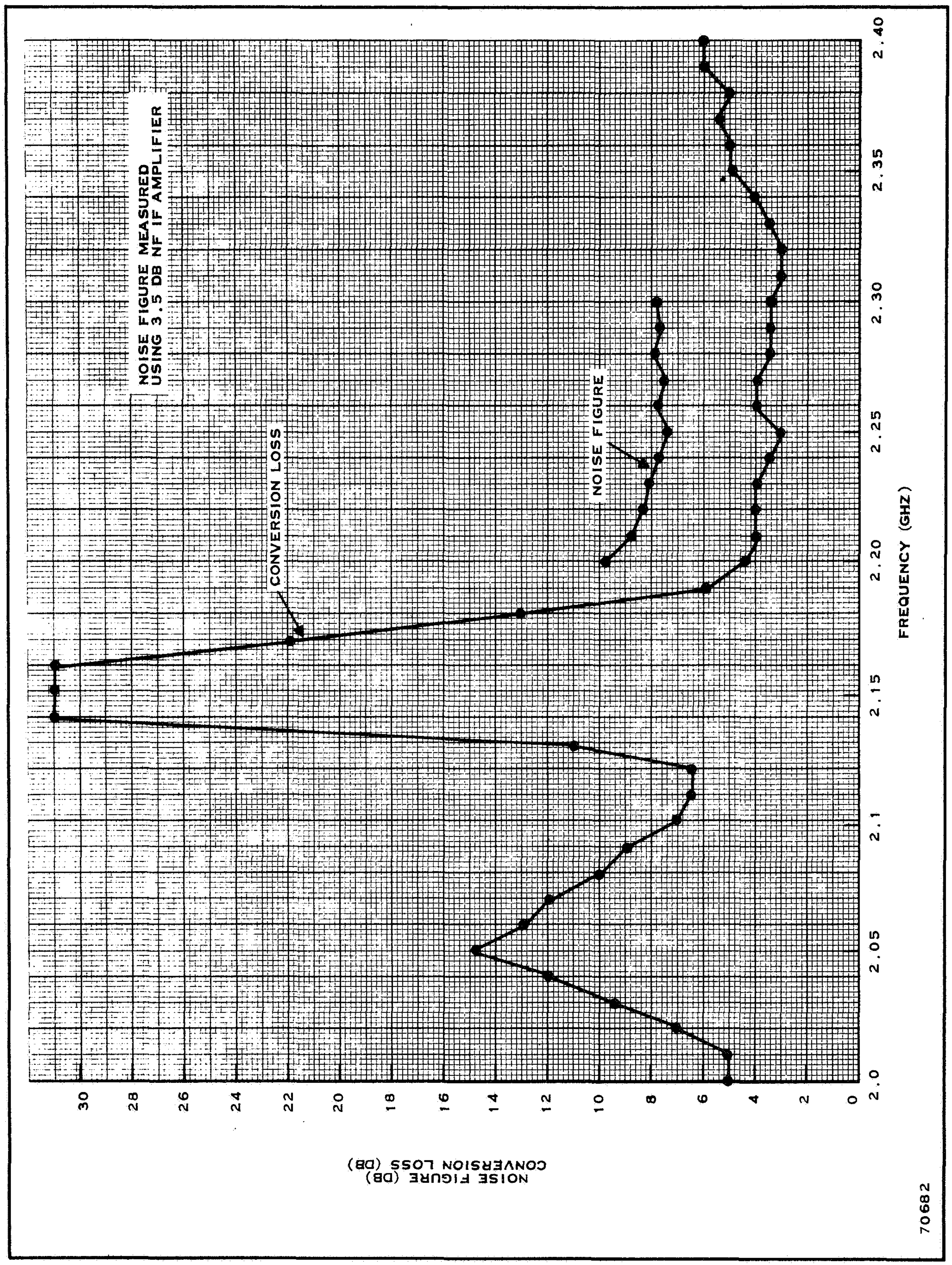

Figure 5. Conversion Loss and Noise Figure Versus Frequency

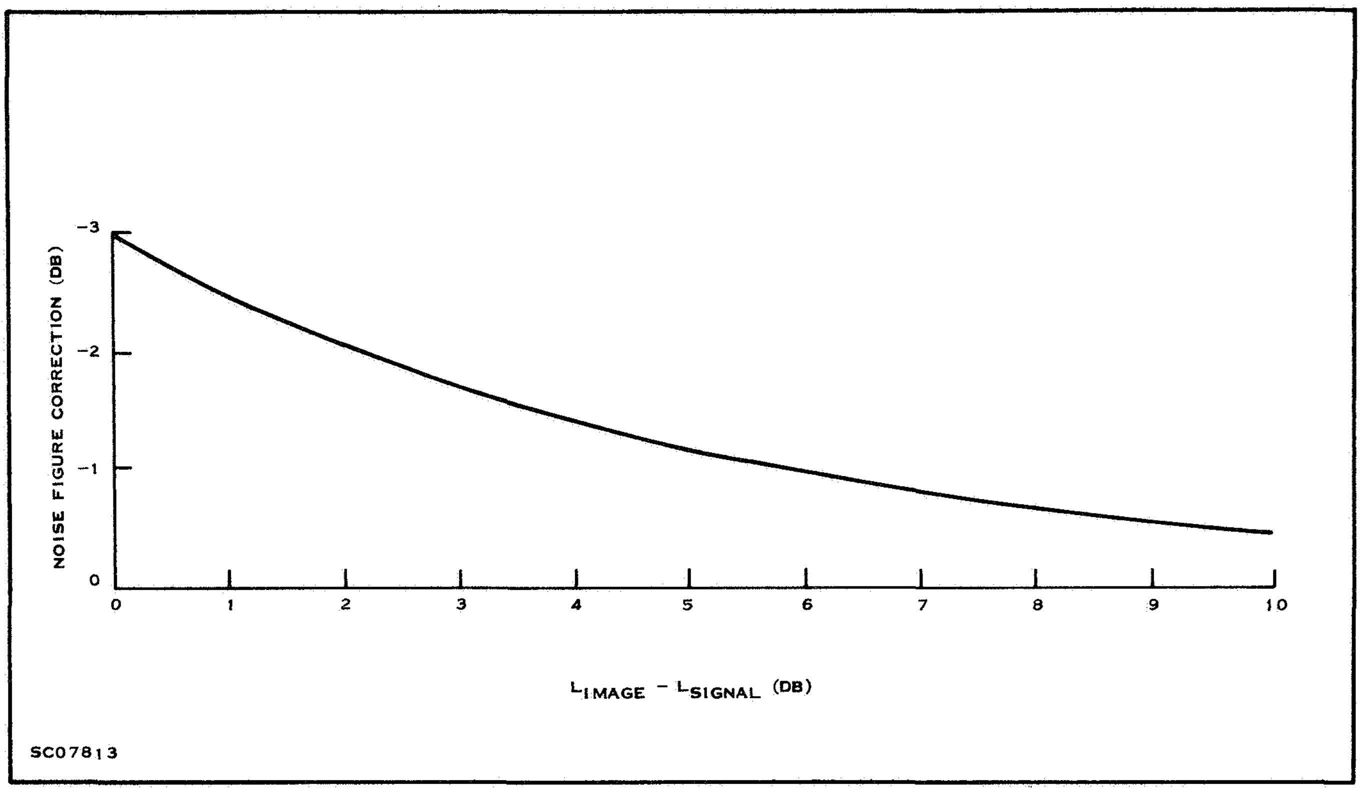

Figure 6. Degradation of Noise Figure Versus Relative Image Conversion Loss

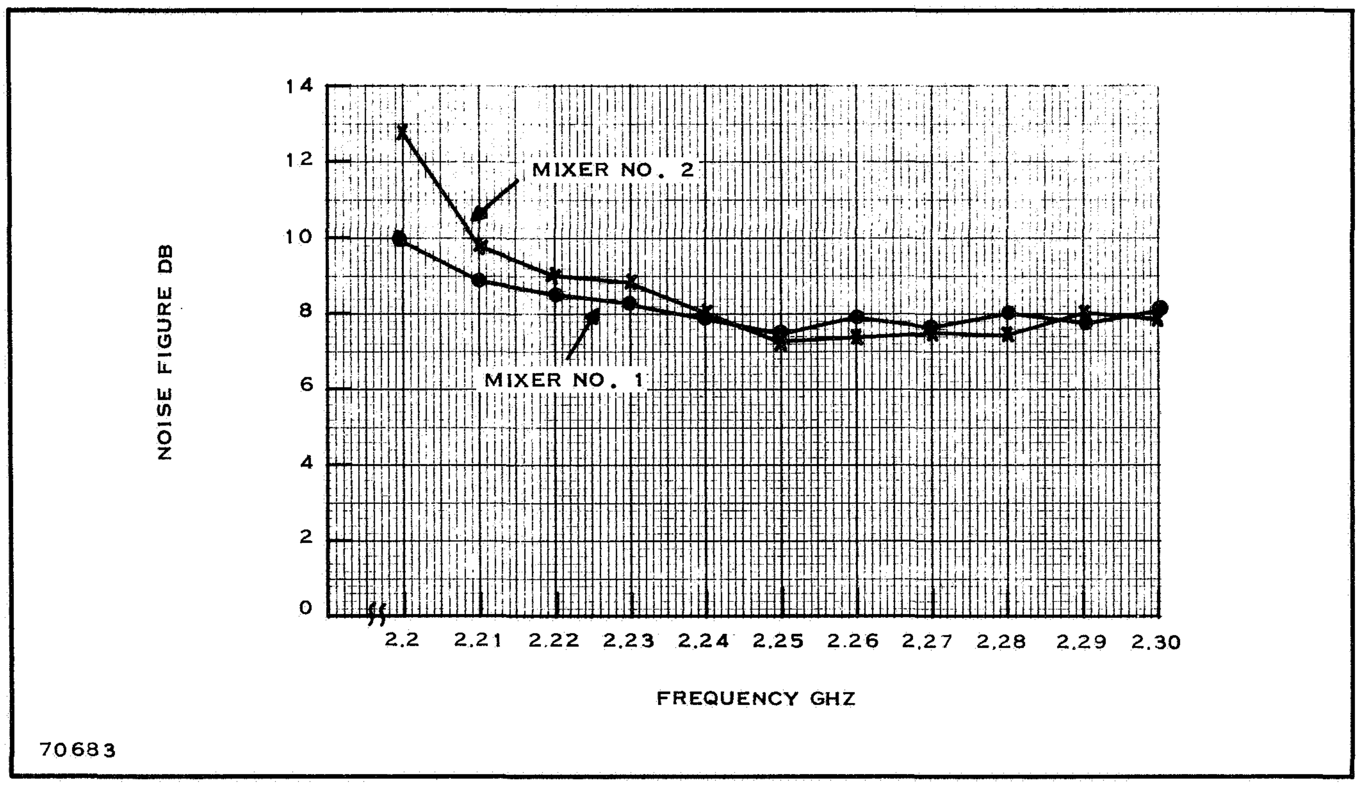

Figure 7. Noise Figure Versus Frequency—Mixers 1 and 2

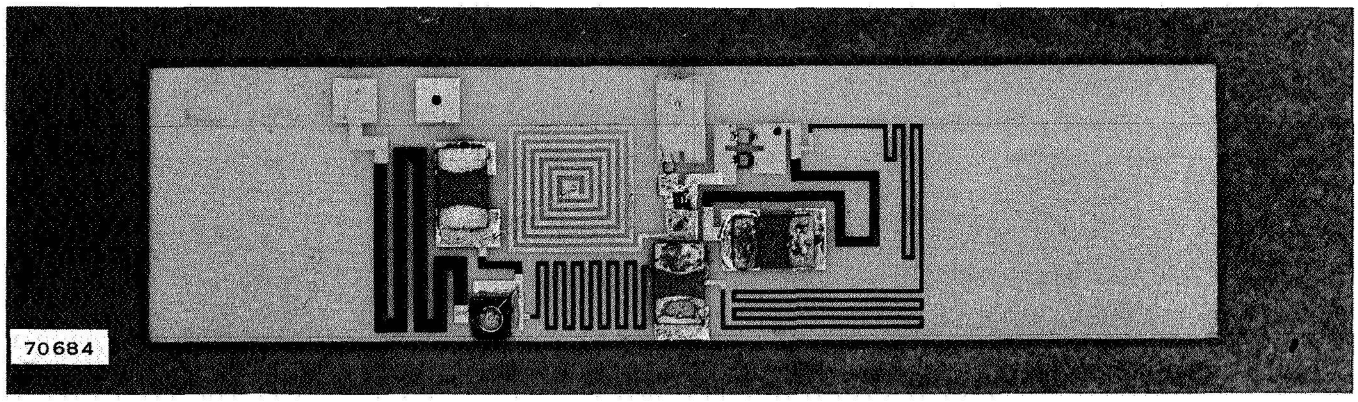

Figure 8. Thin-Film 100-MHz IF Amplifier

The 100-MHz amplifier was constructed using thin-film techniques and chip components. The resulting circuits are shown in Figure 8. Two amplifiers were constructed and tested with the following results

	Circuit 1	*Circuit 2*
Gain	15 dB	18 dB
Noise Figure	4.0 dB	3.5 dB
Bandwidth 3 dB	14 MHz	20 MHz

3. Preselector Filter

The preselector filter was designed with the aid of a computer program. To make the filter design task easier, a 0.5-dB loss was allowed in the desired passband. The desired filter response is shown in Figure 9. The computer program resulted in an 11-element filter shown in Figure 10. The filter response obtained by the computer program and the filter's actual response are shown in Figure 11. From the curve of the actual response shown in Figure 11, it can be seen that the bandpass of the filter is not wide enough and the insertion loss is high. By judiciously tuning the filter with small pieces of gold-plated ceramic, the tuned response shown in Figure 11 was obtained. The final filter is shown in Figure 12.

C. Receiver Integration and Test Results

Upon the successful completion of the mixer, IF amplifier, and preselector filters, the three units were integrated to form the receiver. The amplifier, mixer, and preselector filter were mounted in a gold-plated Kovar housing measuring approximately 2.3 X 1.8 X 0.25 inches. The substrates were attached to the housing using a low-temperature solder. Each receiver weighs approximately 2.4 ounces. The finished receivers are shown in Figure 13. After being built, the two receivers were tested to Paragraphs 3.1, 3.2, 3.3, 3.5, and 3.9 of the Receiver Test Procedure. These tests are:

Paragraph 3.1 Sensitivity

Paragraph 3.2 Dynamic Range

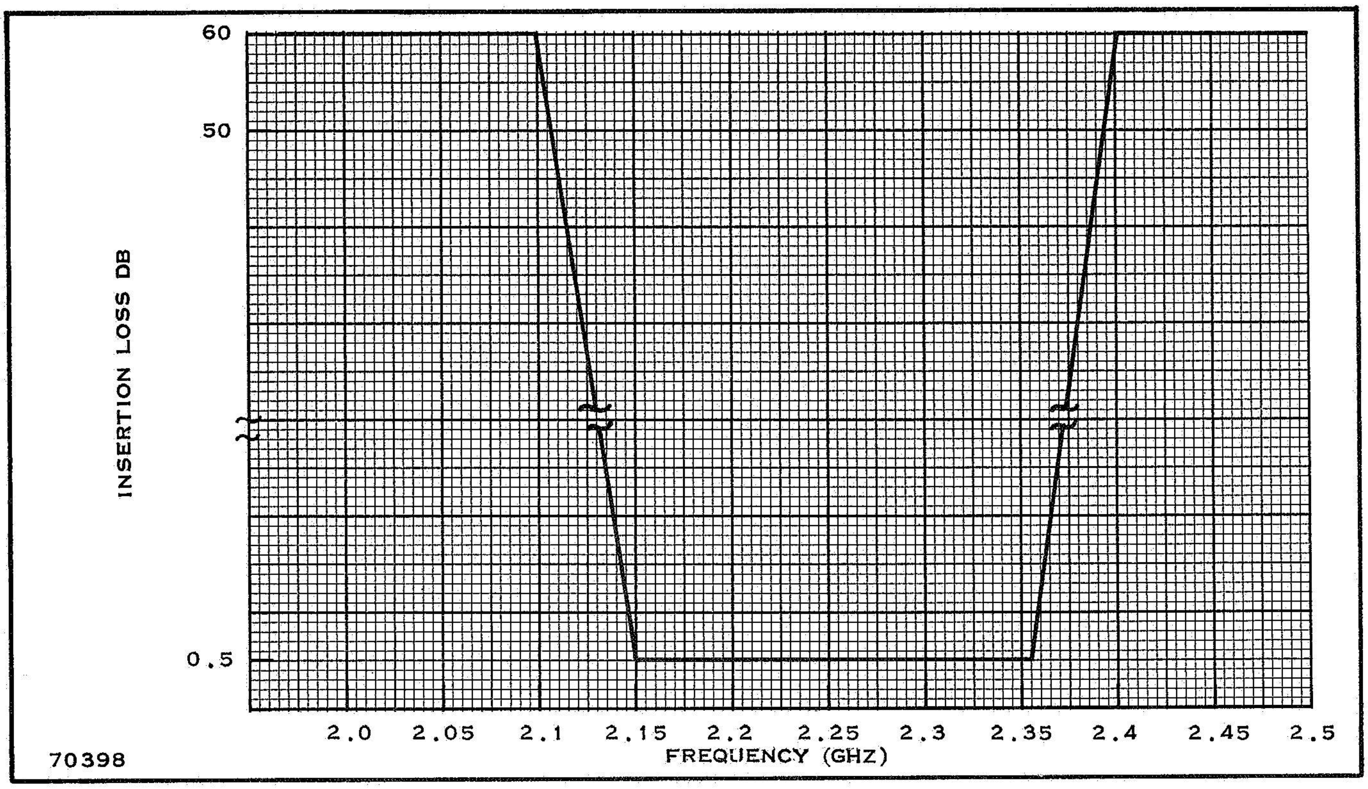

Figure 9. Ideal Preselector Filter Response

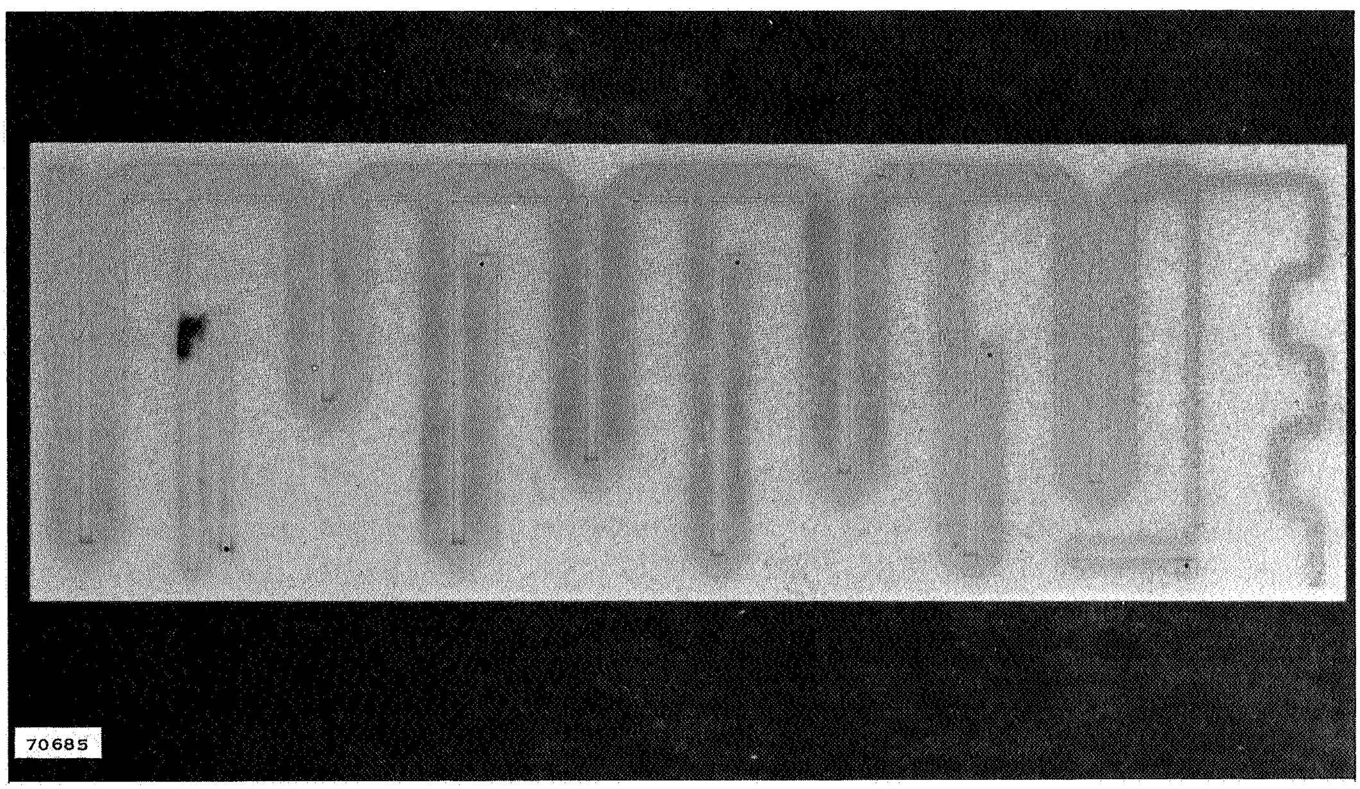

Figure 10. Preselector Filter

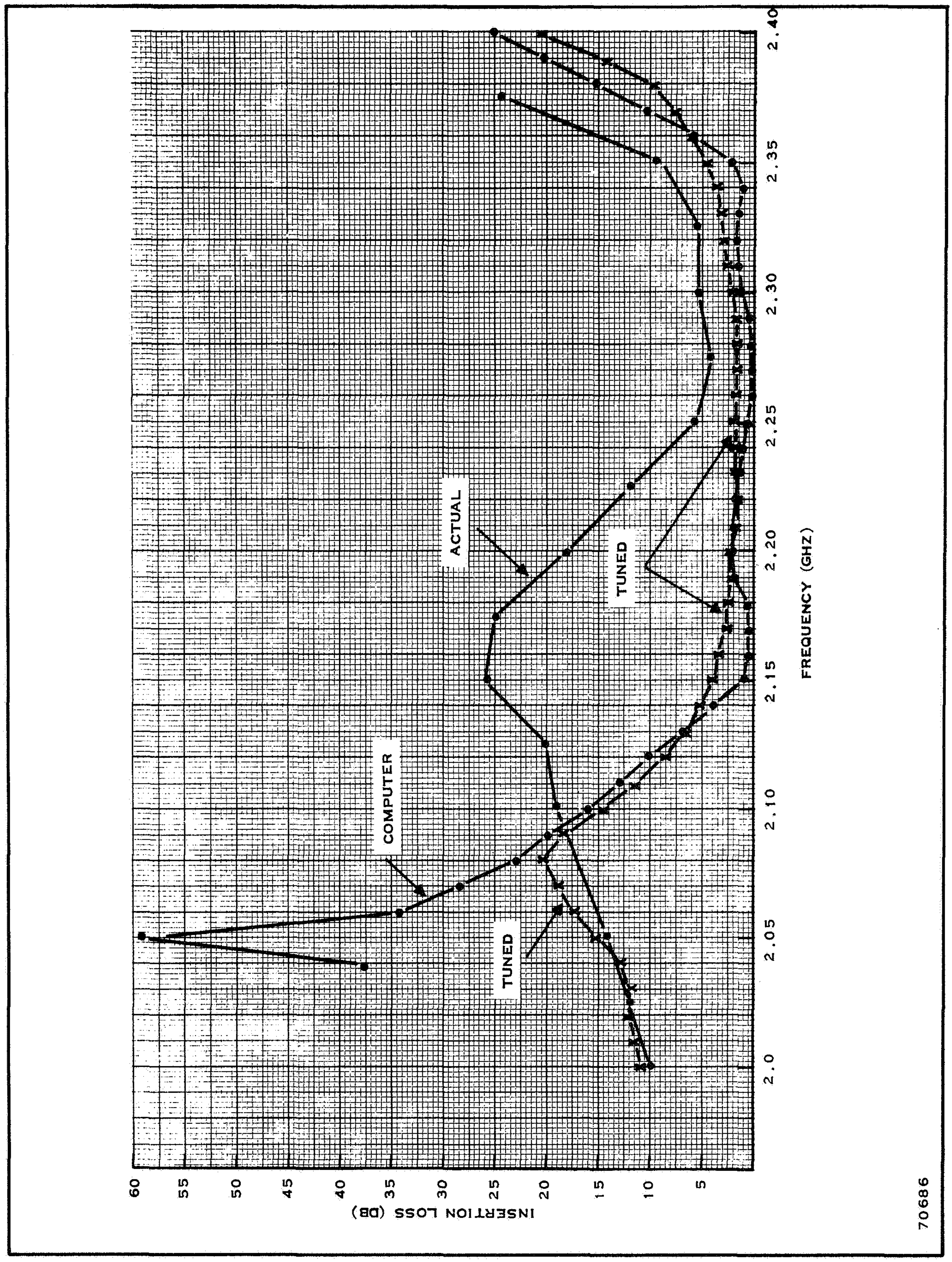

Figure 11. Preselector Filter Response

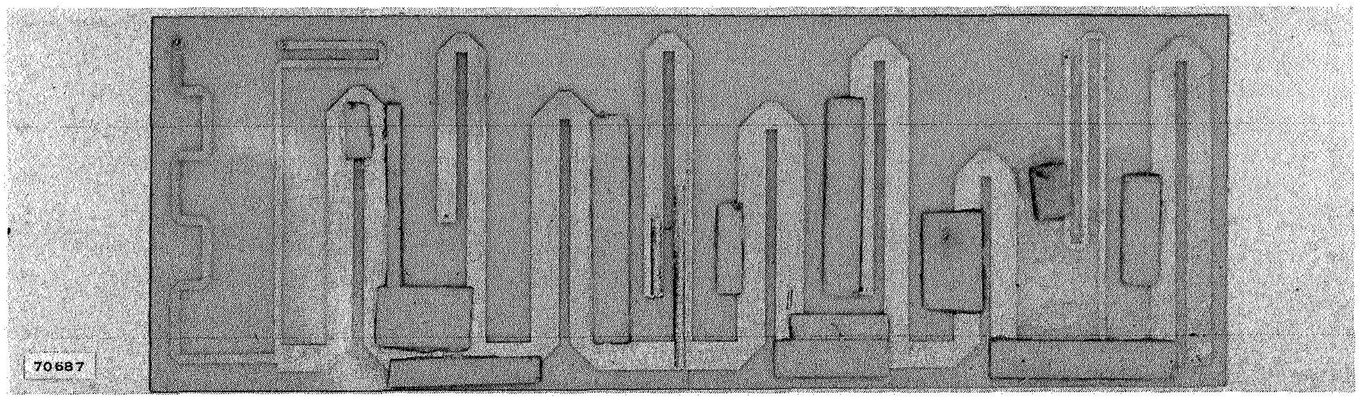

Figure 12. Preselector Filter with Tuning Chips

Paragraph 3.3 Image Rejection

Paragraph 3.5 Noise Figure

Paragraph 3.9 Bandwidth

The results of the above tests are presented in the following paragraphs.

1. Noise Figure

Using the Hewlett-Packard 342A Noise Figure Meter and the Hewlett-Packard 349A Noise Source, the noise figure of each receiver was measured.

Receiver No. 1 Noise Figure = 12 dB

Receiver No. 2 Noise Figure = 11 dB.

Since the noise figure of the receivers was expected to be between 9.0 and 10.0 dB (from individual block tests), it appears that a mismatch between the preselector output and the mixer input and a mismatch between the mixer 100-MHz output and the IF input exist and are contributing approximately 2 dB of loss.

2. Bandwidth

The receiver 3-dB IF bandwidth was measured by maintaining a constant local oscillator frequency and measuring the frequency on each side of the 2.250-GHz reference frequency where the output level of the IF has decreased by 3 dB.

	3 dB B.W.
Receiver No. 1	31.86 MHz
Receiver No. 2	22.31 MHz

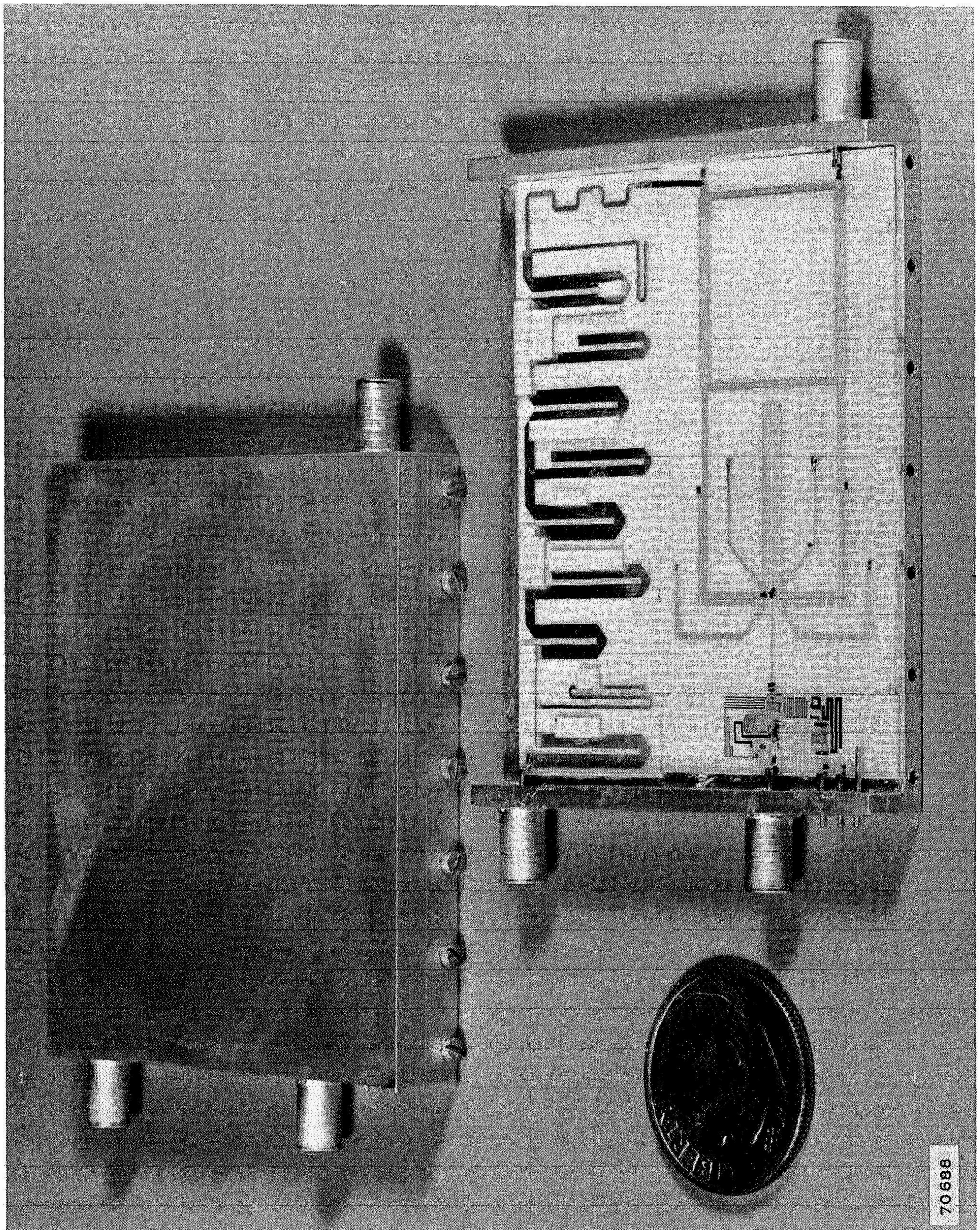

Figure 13. Final Receivers

3. Image Rejection

The receiver image rejection was measured by measuring the difference in the necessary input level for a signal at the desired frequency of 2.25 GHz and one at the image frequency of 2.05 GHz for a given IF output level.

	Image Rejection
Receiver No. 1	–23 dB
Receiver No. 2	–21 dB

4. Sensitivity and Dynamic Range

The receiver sensitivity and dynamic range for the IF bandwidths and noise figures previously determined were determined by measuring the output level of the receiver for each 1.0-dB increase in input level until the output level was compressed by 1.0 dB from the straight line projection. The plot of receiver dynamic range is shown in Figures 14 and 15. The sensitivity can be determined by choosing any desired signal-to-noise ratio at the output and reading the corresponding input level.

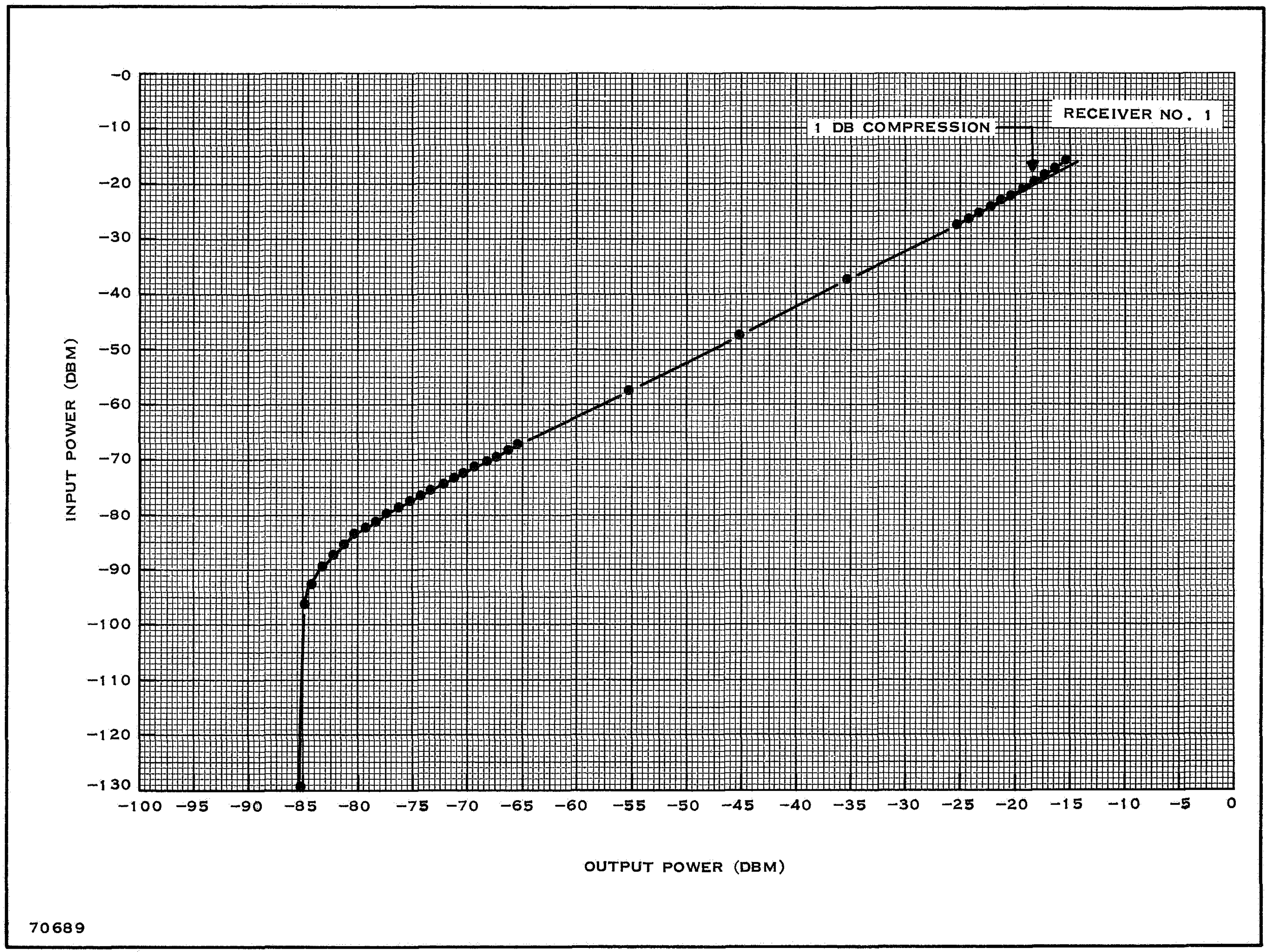

Figure 14. Determination of Receiver Sensitivity and Dynamic Range–Receiver No. 1

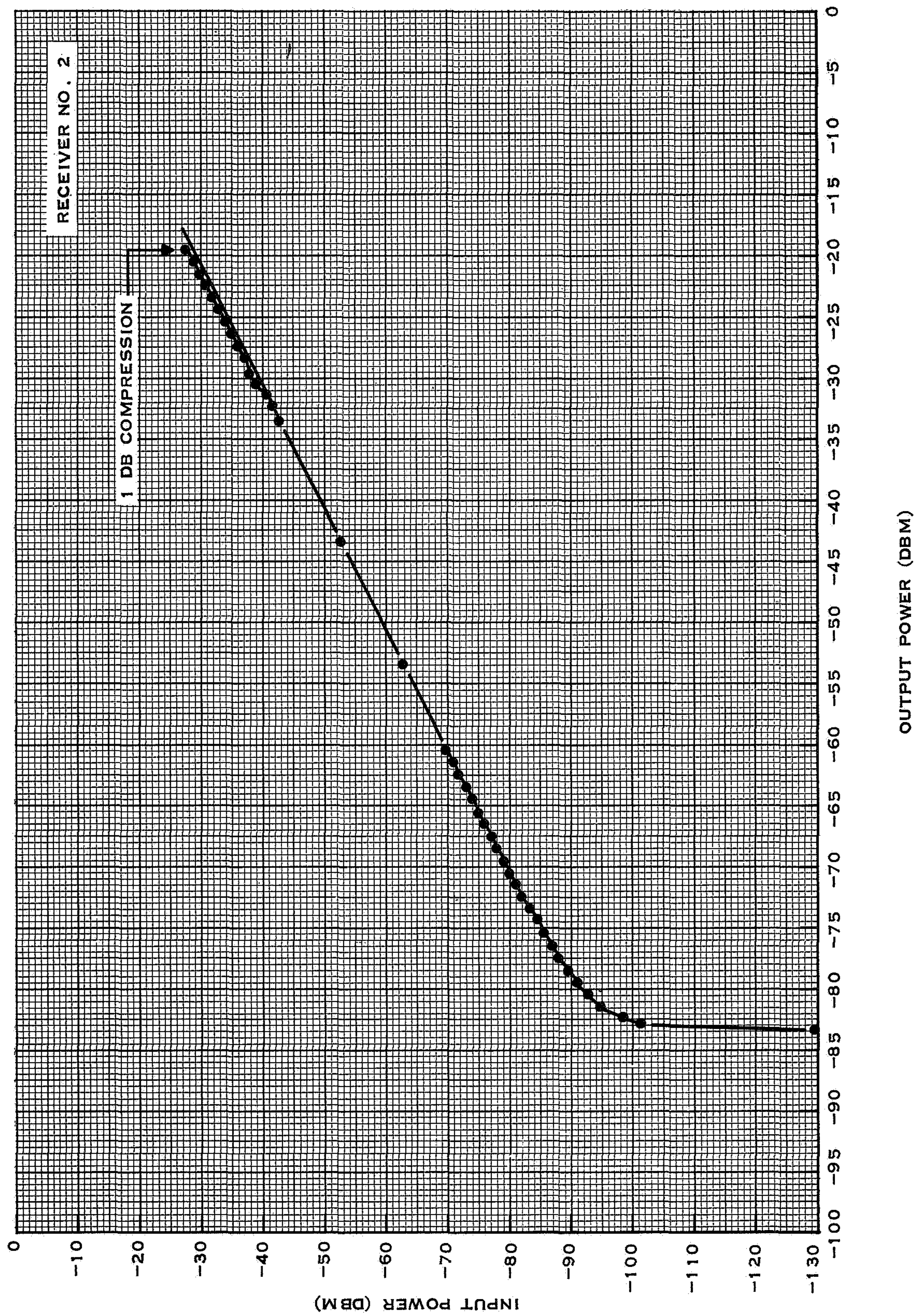

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Figure 15. Determination of Receiver Sensitivity and Dynamic Range–Receiver No. 2

SECTION IV

TRANSMITTER

A. General

The transmitter consists of a modulator, voltage-controlled oscillator (VCO), and a power amplifier chain. The minimum output power is 0.5 watt over a tunable-frequency band of 2.2 to 2.3 GHz. The general transmitter performance parameters are shown in Table II.

The design and development of the VCO/modulator and class A buffer amplifier was covered in Scientific Report No. 6. Additional device characterization permitted the completion of all interstage and output matching networks.

With the successful fabrication and test of the VCO/modulator/buffer amplifier and power amplifier circuits, two transmitters were fabricated and tested.

B. Circuit Design and Analysis

1. VCO/Amplifier

Since the design of the VCO and buffer amplifier was covered in Scientific Report No. 6, it will not be repeated here. Two substrates were fabricated and checked. Since it is not possible to determine the exact length of the oscillator emitter tab and the exact output tap point on the collector line until the driver and buffer amplifiers are mated, the oscillator/amplifier circuits were checked for nominal output power across the band of interest. The two circuits which were fabricated had nominal output powers of 225 mW.

2. Power Amplifier

Due to the difficulties experienced with the L-158A devices, the output power requirement was reduced to 0.5 watt. This reduction permitted two L-158C devices operating in parallel to be used in the final power amplifier stage. Because of the new final amplifier configuration, additional device characterization was necessary. The characterization technique used employed ceramic test circuits and is described in Scientific Report No. 5 (Report No. U27-811500-27). The results of the characterization are shown in Figure 16.

Using the new characterization data, the computer matching program was used to design the interstage networks between the driver and final amplifiers and between the final amplifier and the 50-ohm output. The network responses are shown in Figures 17 and 18.

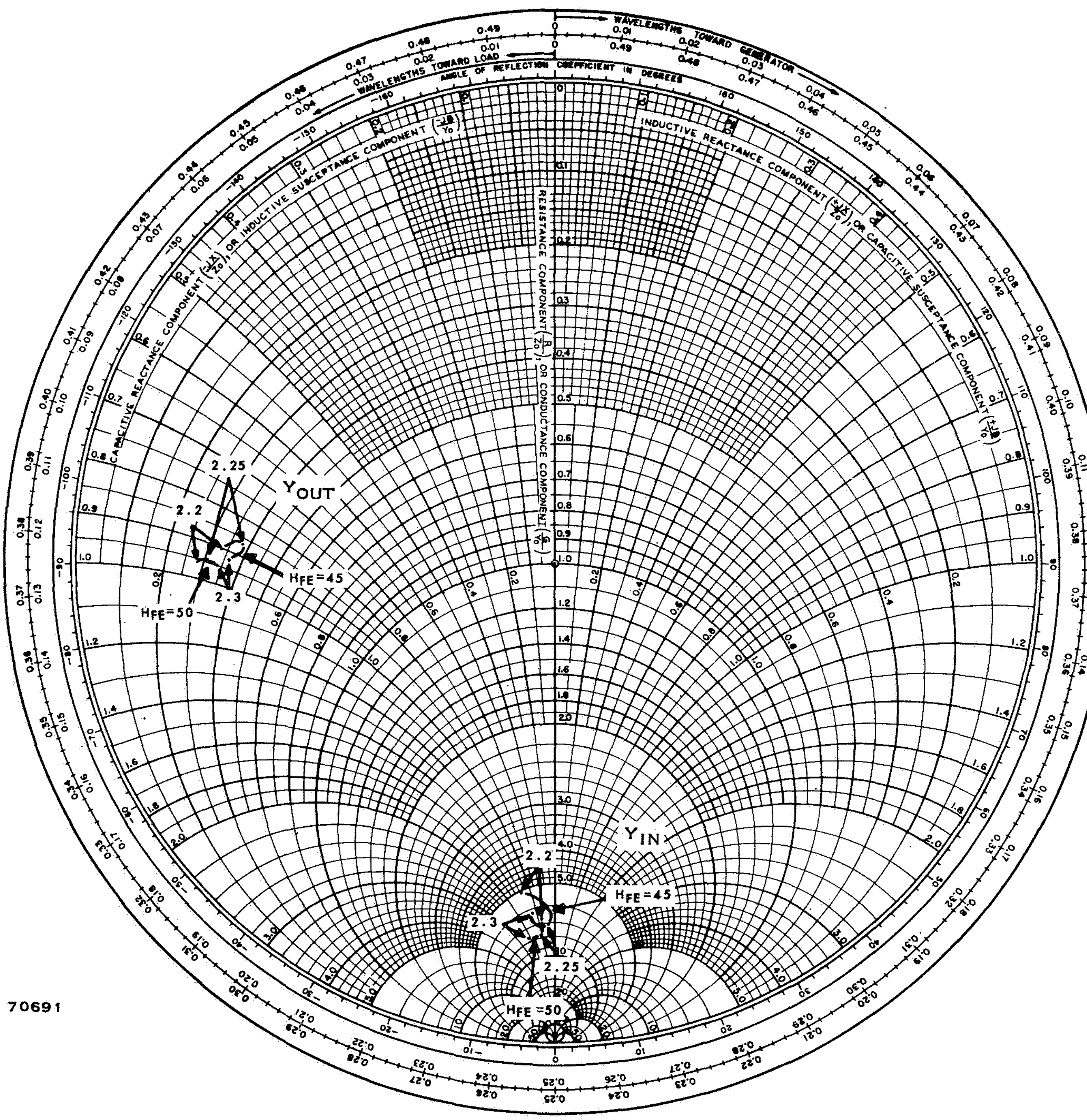

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Figure 16. Characterization Data

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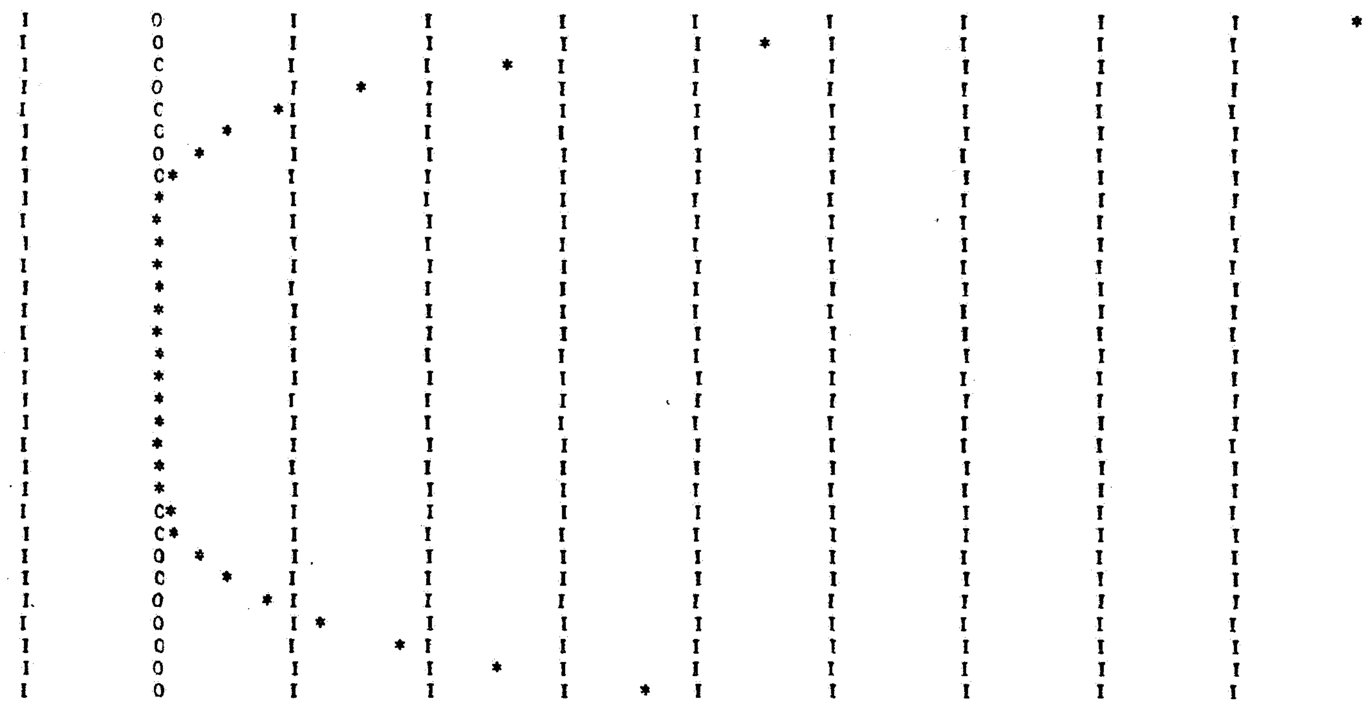
FREQUENCY      POWER LOSS
   GHZ             DB

    2.100        100.000    I         0         I         I         I         I         I         I         I         I       *
    2.110        100.000    I         0         I         I         I         I         I         I         I         I       *
    2.120        100.000    I         0         I         I         I         I         I         I         I         I       *
    2.130        100.000    I         0         I         I         I         I         I         I         I         I       *
    2.140          7.511    I         0         I         I         I         I         I         I         I   *     I
    2.150          2.434    I         0         I         I   *     I         I         I         I         I         I
    2.160          1.321    I         0         I  *      I         I         I         I         I         I         I
    2.170          0.856    I         0       * I         I         I         I         I         I         I         I
    2.180          0.558    I         0    *    I         I         I         I         I         I         I         I
    2.190          0.422    I         0   *     I         I         I         I         I         I         I         I
    2.200          0.286    I         0 *       I         I         I         I         I         I         I         I
    2.210          0.178    I         0*        I         I         I         I         I         I         I         I
    2.220          0.095    I         *         I         I         I         I         I         I         I         I
    2.230          0.037    I         *         I         I         I         I         I         I         I         I
    2.240          0.006    I         *         I         I         I         I         I         I         I         I
    2.250          0.001    I         *         I         I         I         I         I         I         I         I
    2.260          0.017    I         *         I         I         I         I         I         I         I         I
    2.270          0.047    I         *         I         I         I         I         I         I         I         I
    2.280          0.084    I         *         I         I         I         I         I         I         I         I
    2.290          0.120    I         0*        I         I         I         I         I         I         I         I
    2.300          0.148    I         0*        I         I         I         I         I         I         I         I
    2.310          0.161    I         0*        I         I         I         I         I         I         I         I
    2.320          0.155    I         0*        I         I         I         I         I         I         I         I
    2.330          0.129    I         0*        I         I         I         I         I         I         I         I
    2.340          0.090    I         *         I         I         I         I         I         I         I         I
    2.350          0.053    I         *         I         I         I         I         I         I         I         I
    2.360          0.068    I         *         I         I         I         I         I         I         I         I
    2.370          0.291    I         0 *       I         I         I         I         I         I         I         I
    2.380          1.444    I         0         I   *     I         I         I         I         I         I         I
    2.390        100.000    I         0         I         I         I         I         I         I         I         I       *
    2.400        100.000    I         0         I         I         I         I         I         I         I         I       *
```

ELEMENT	TYPE	YZ	BL	WIDTH	LENGTH
1	FAT SERIES SECTION	14.2	57.6	10.3	353.7
2	SHORTED STUB	10.8	128.5	4.8	804.9
3	GENERAL SERIES SECTION	14.5	10.0	10.9	61.2

Figure 17. Matching Network Response (Driver Output to Final Input)

FREQUENCY GHZ	POWER LOSS DB
2.100	9.143
2.110	4.517
2.120	2.609
2.130	1.552
2.140	0.922
2.150	0.536
2.160	0.302
2.170	0.161
2.180	0.080
2.190	0.037
2.200	0.015
2.210	0.007
2.220	0.005
2.230	0.005
2.240	0.006
2.250	0.006
2.260	0.004
2.270	0.003
2.280	0.003
2.290	0.008
2.300	0.023
2.310	0.053
2.320	0.106
2.330	0.194
2.340	0.330
2.350	0.533
2.360	0.827
2.370	1.240
2.380	1.810
2.390	2.587
2.400	3.640



ELEMENT	TYPE	YZ	BL	WIDTH	LENGTH
1	FAT SERIES SECTION	10.0	12.6	3.6	79.3
2	SHORTED STUB	11.8	23.2	6.4	144.4
3	GENERAL SERIES SECTION	13.9	11.3	9.8	69.2

Figure 18. Matching Network Response (Final Output to 50 Ohm)

TABLE II. FM TELEMETRY TRANSMITTER PERFORMANCE PARAMETERS

See Page 2

A. **Frequency**: 2.2 to 2.3 GHz

B. **Frequency Stability**: ±0.5 Percent (Without AFC Circuitry) over Temperature Range

C. **Modulation**:

1.	Type	FM and/or FSK
2.	Linearity	1 percent for FM
3.	Baseband	2 kHz to 1.0 MHz
4.	Sensitivity	0.2 V rms/100 kHz
5.	Deviation	±1.5 MHz
6.	Input impedance	600 ohms
7.	Output impedance	50 ohms

to 50°C

Δf ≈ .01%/°C

D. **Power Output**: 0.5 Watt

E. **DC Input**: Negative 24.5 Volts

F. **Efficiency (dc to RF)**: 10 Percent to 20 Percent

G. **Size**: Approximately 1 X 2 X 1/4 inches

H. **Weight**: Approximately 3 ounces

Circuits were fabricated and tested using the above-mentioned networks. However, the bandpass of the networks was approximately 200 MHz low and it was necessary to modify the matching networks. The final amplifier circuitry is shown in Figure 19. Since it is desirable to have some resistance in the emitter circuitry for good class C operation, Nichrome resistance wire was used in the dc emitter path. Since the necessary resistance was less than 10 ohms, this prompted the use of resistance wire over thin-film resistors and the use of resistance wire allowed the emitter resistor to be adjusted, thereby controlling the stage gain and current.

C. Integration

Two power amplifier circuits were fabricated and then integrated with the two oscillator/amplifier circuits. During the integration process, the emitter tab and tap point on the oscillator were adjusted for best operation. During this initial mating, a dc block was used between the output of the buffer amplifier and the input to the driver amplifier. The test results after mating the circuits are shown in Tables III and IV.

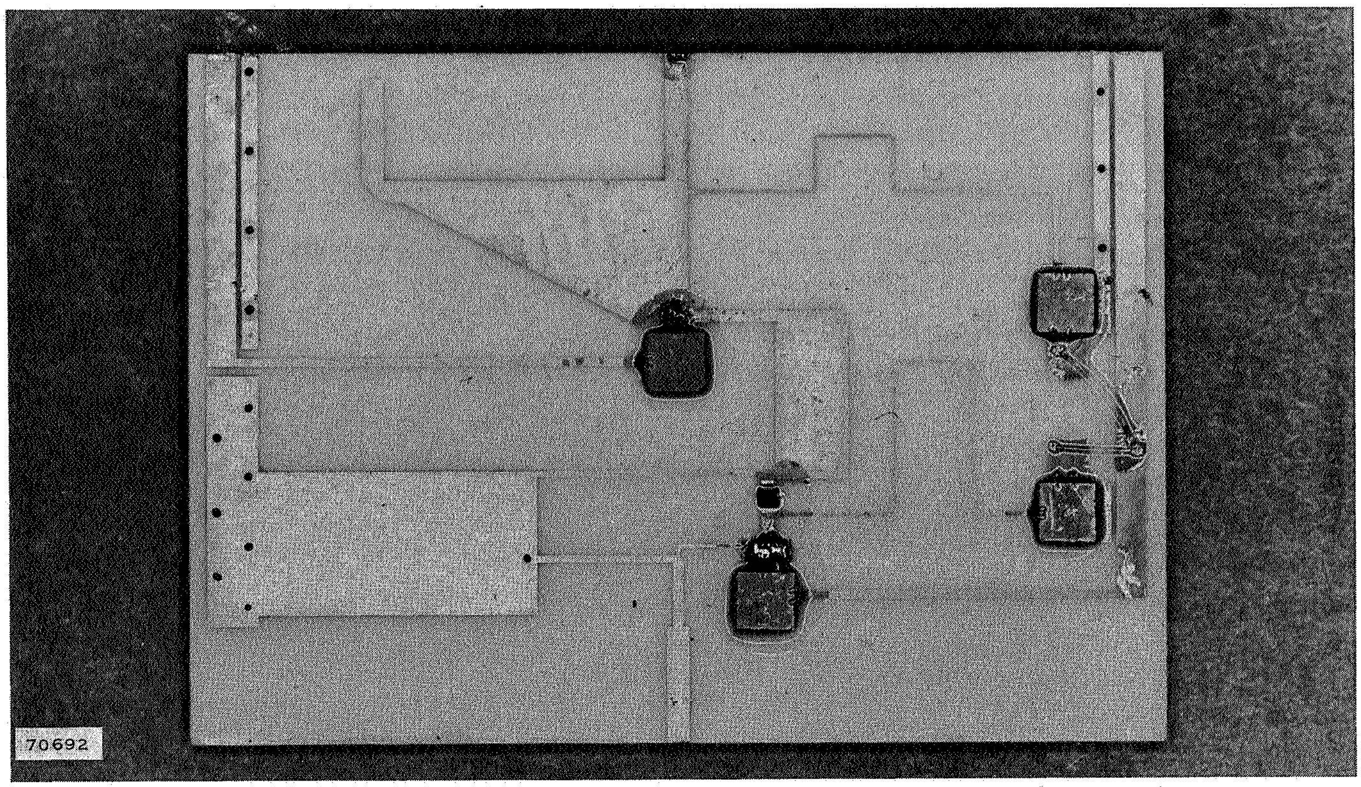


Figure 19. Final Power Amplifier Configuration

Once the oscillator/amplifier and power amplifier circuits had been successfully mated, they were mounted in the transmitter housing using low-temperature solder to secure the substrates. In this final configuration, a 100-pF beam lead capacitor is used as a dc block between the buffer and driver amplifiers. The final transmitter package measures approximately 2.2 X 1.1 X 0.3 inches, including connectors. The total weight is approximately 1.3 ounces. The final transmitters are shown in Figure 20. Transmitter No. 1 is composed of Oscillator/Amplifier No. 2 and Power Amplifier No. 1 (see data in Table III). Transmitter No. 2 is composed of Oscillator/Amplifier No. 3 and Power Amplifier No. 5 (see data in Table IV).

TABLE III. POWER OURPUR VERSUS FREQUENCY OSCILLATOR/AMPLIFIER NO. 2–POWER AMPLIFIER NO. 1

Frequency (GHz)	Output Power (mW)	Varactor Voltage (volts)	I_{total} (mA)	V_T (Volts)
2.10	330	7.8	242	–24.5
2.11	420	8.1	245	–24.5
2.12	480	8.3	246	–24.5
2.13	520	8.5	248	–24.5
2.14	560	8.7	249	–24.5
2.15	580	9.0	250	–24.5
2.16	630	9.5	255	–24.5
2.17	710	10.0	260	–24.5
2.18	725	10.5	260	–24.5
2.19	745	10.9	260	–24.5
2.20	760	11.3	260	–24.5
2.21	770	11.7	259	–24.5
2.22	780	12.0	257	–24.5
2.23	770	12.5	255	–24.5
2.24	765	12.9	254	–24.5
2.25	760	13.2	252	–24.5
2.26	730	13.7	250	–24.5
2.27	710	14.2	247	–24.5
2.28	680	14.8	242	–24.5
2.29	660	15.5	242	–24.5
2.30	620	16.2	240	–24.5
2.31	600	17.0	240	–24.5
2.32	560	18.0	240	–24.5
2.33	530	19.0	236	–24.5
2.34	490	20.4	235	–24.5
2.35	450	22.0	232	–24.5

TABLE IV. POWER OUTPUT VERSUS FREQUENCY OSCILLATOR/AMPLIFIER NO. 3–POWER AMPLIFIER NO. 5

Frequency (GHz)	Output Power (mW)	Varactor Voltage (volts)	I_{total} (mA)	V_T (Volts)
2.17	920	5.6	258	–24.5
2.18	870	8.2	262	–24.5
2.19	890	8.7	262	–24.5
2.20	920	9.2	262	–24.5
2.21	940	9.5	262	–24.5
2.22	970	10.0	262	–24.5
2.23	1000	10.3	262	–24.5
2.24	1030	10.7	262	–24.5
2.25	1030	11.1	261	–24.5
2.26	1020	11.5	260	–24.5
2.27	1000	12.0	259	–24.5
2.28	970	12.5	255	–24.5
2.29	940	13.1	254	–24.5
2.30	910	13.6	252	–24.5
2.31	880	14.3	250	–24.5
2.32	840	15.0	250	–24.5
2.33	800	15.7	250	–24.5
2.34	760	16.6	249	–24.5
2.35	710	17.6	249	–24.5
2.36	660	18.6	247	–24.5
2.37	610	20.0	246	–24.5

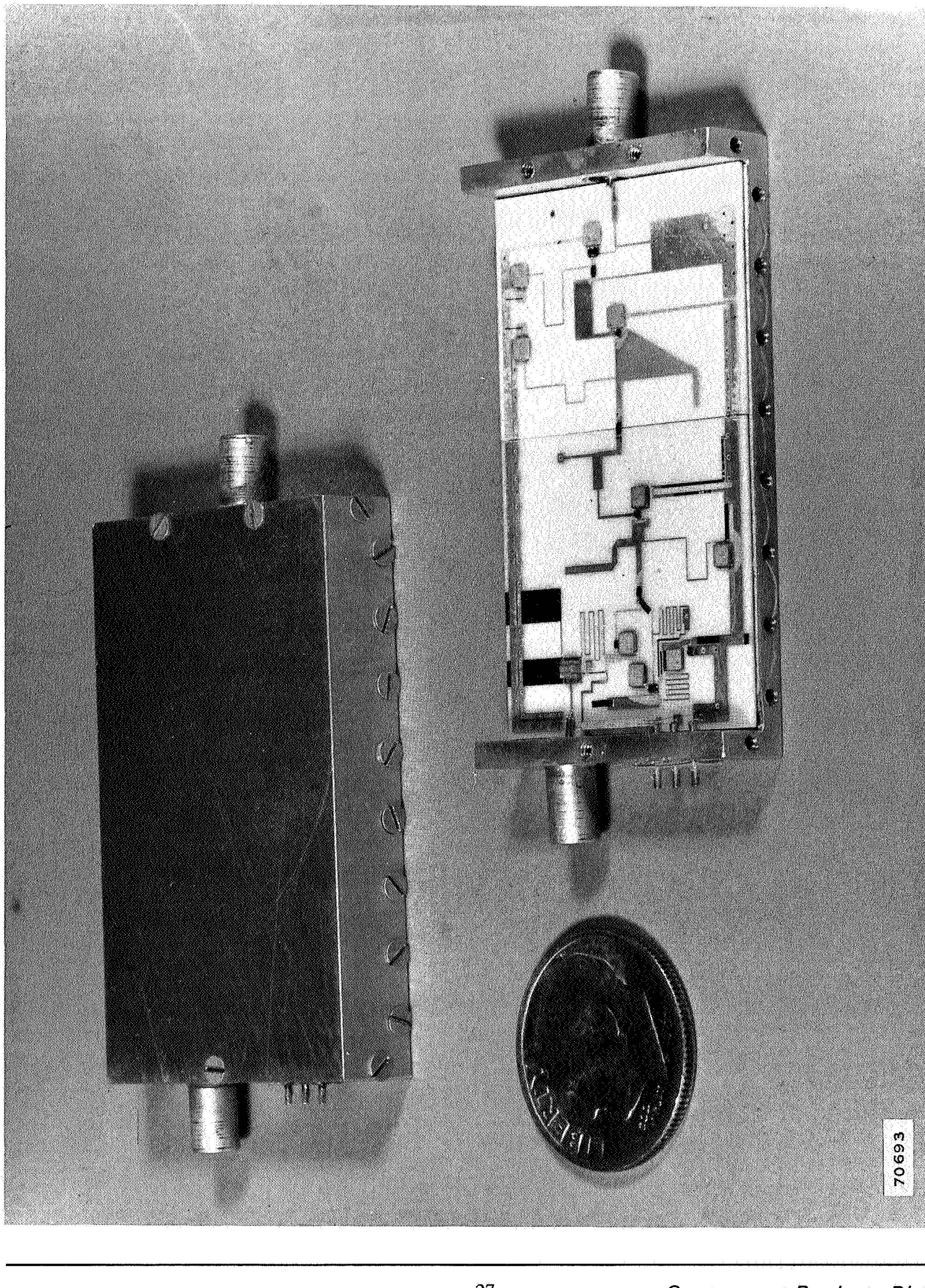


Figure 20. Final Transmitters

D. Test Results

The two transmitters were tested to Paragraphs 1 through 7 of the Transmitter Test Plan (see Appendix B, Scientific Report No. 5). The results of those tests are presented in the following paragraphs.

1. Transmitter No. 1

a. Size and Weight — 2.2 X 1.1 X 0.27 inches; 1.3 ounces

b. Center Frequency Stability

Starting Frequency:	2.250037 GHz
Frequency after 30 minutes:	2.249726 GHz
Percent = 0.014 Δf	311 kHz

c. Power Output Versus Frequency

The transmitter output frequency is varied in 10-MHz steps by varying the varactor voltage. The output power, varactor voltage, frequency, and transmitter current are measured at each 10-MHz increment.

Frequency (GHz)	Power Out (mW)	Varactor Voltage (volts)	I_{total} (mA)	Supply Voltage (volts)
2.10	410	8.6	257	–24.5
2.11	460	8.8	260	–24.5
2.12	500	9.0	260	–24.5
2.13	530	9.3	263	–24.5
2.14	560	9.7	263	–24.5
2.15	590	10.2	263	–24.5
2.16	600	10.6	263	–24.5
2.17	620	11.2	263	–24.5
2.18	630	11.8	263	–24.5
2.19	650	12.2	264	–24.5
2.20	680	12.6	265	–24.5
2.21	680	13.0	265	–24.5
2.22	750	13.5	266	–24.5
2.23	780	14.0	263	–24.5
2.24	800	14.7	260	–24.5
2.25	770	15.3	256	–24.5
2.26	750	16.0	252	–24.5
2.27	710	16.7	248	–24.5
2.28	670	17.6	243	–24.5
2.29	620	18.4	240	–24.5
2.30	570	19.3	235	–24.5
2.31	530	20.4	232	–24.5
2.32	480	21.6	229	–24.5
2.33	430	23.0	225	–24.5

A plot of the power output versus frequency is shown in Figure 21.

d. Efficiency

2.20 GHz–10.5 percent

2.25 GHz–12.2 percent

2.30 GHz–9.9 percent

e. Modulation Characteristics

(1) Modulation Frequency Response

The modulation voltage V_m is measured at different modulation frequencies f_m for a constant deviation of 300 kHz.

f_m (kHz)	f_0 = 2.20 GHz V_m (volts)	f_0 = 2.25 GHz V_m (volts)	f_0 = 2.30 GHz V_m (volts)	Deviation kHz
14.143	0.405	0.72	1.10	300
16.601	0.41	0.72	1.10	300
20.093	0.41	0.72	1.10	300
25.442	0.41	0.72	1.10	300
34.667	0.405	0.72	1.10	300
54.347	0.405	0.73	1.10	300
124.75	0.41	0.72	1.10	300
300.00	0.425	0.71	1.12	300
500.00	0.45	0.74	1.12	300
1000.00	0.52	0.85	1.14	300

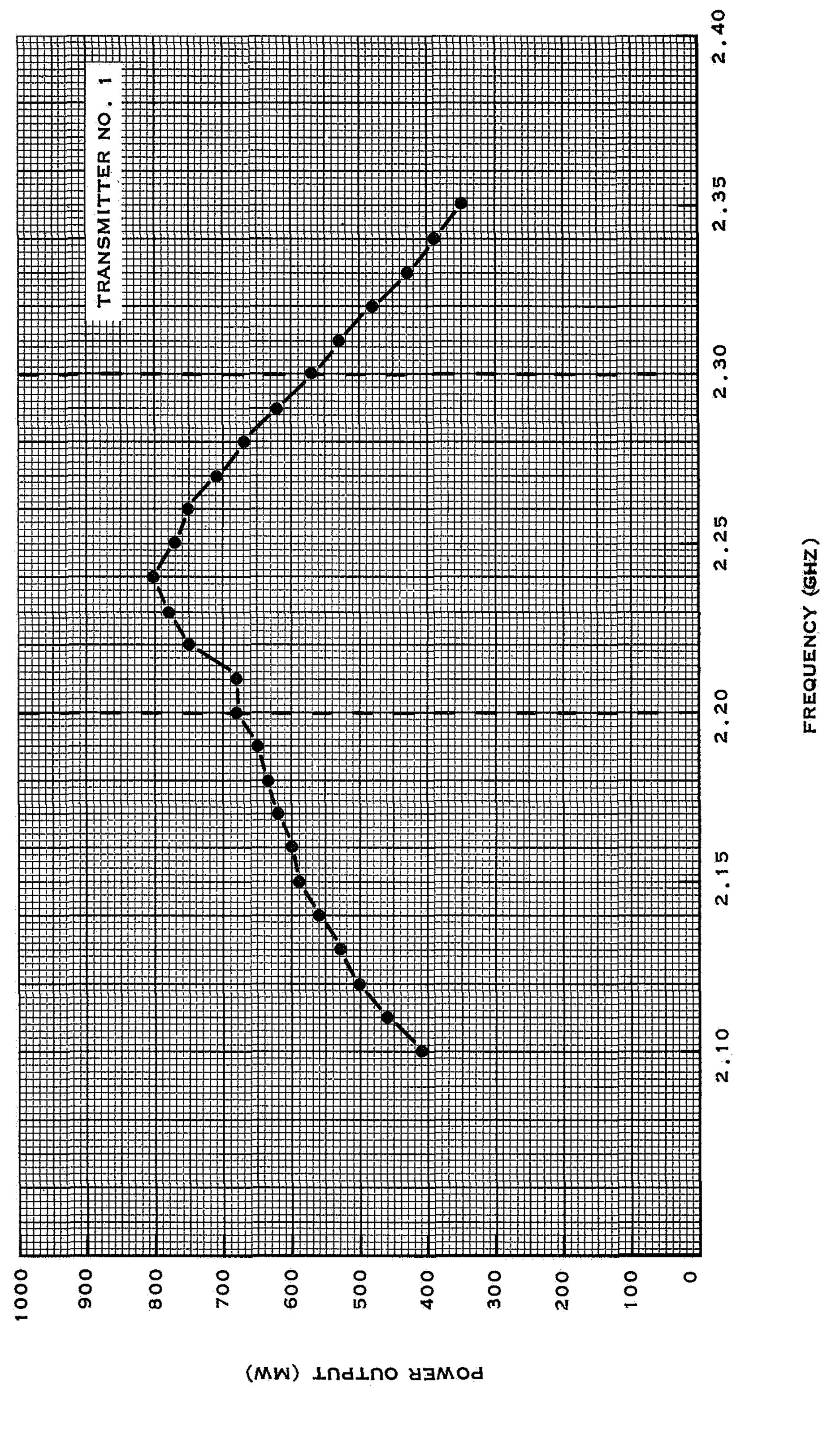


Figure 21. Transmitter No. 1–Power Output Versus Frequency

A plot of the modulation response is shown in Figure 22.

(2) Deviation Linearity

A constant modulating frequency, 70.716 kHz is used and the required modulation voltage is measured for various deviations.

Peak Deviation (kHz)	Carrier (zero)	f_0 = 2.20 GHz (V_m)	f_0 = 2.25 GHz (V_m)	f_0 = 2.30 GHz (V_m)
170.057	1	0.24	0.40	0.62
390.359	2	0.53	0.92	1.45
611.955	3	0.83	1.45	2.25
833.847	4	1.13	1.98	3.1
1055.853	5	1.45	2.52	3.9
1277.915	6	1.75	3.05	4.7
1500.00	7	2.06	3.57	5.5

A plot of the deviation versus modulation voltage is shown in Figure 23.

(3) Deviation Sensitivity

The deviation sensitivity can be read directly off the curves of Figure 23. The reason for the three different slopes of the deviation curves is due to the change in the varactor operating point as the center frequency is changed. As the varactor voltage is increased, a larger modulation voltage is required because of the varactor characteristics. At the center frequency of 2.25 GHz the deviation sensitivity $\Delta v/\Delta f$ is 0.25 volt per 100 kHz.

f. Input Impedance

The transmitter is deviated a specified amount at a selected modulating frequency with and without a 600-ohm resistor in series with the modulation input. The amplitude of the modulating signal is measured and the input impedance of the transmitter is calculated using the two amplitudes of the modulating signal.

$$Z_{in} = \frac{V_{(5)} \times 600}{V_{(8)} \times V_{(5)}}$$

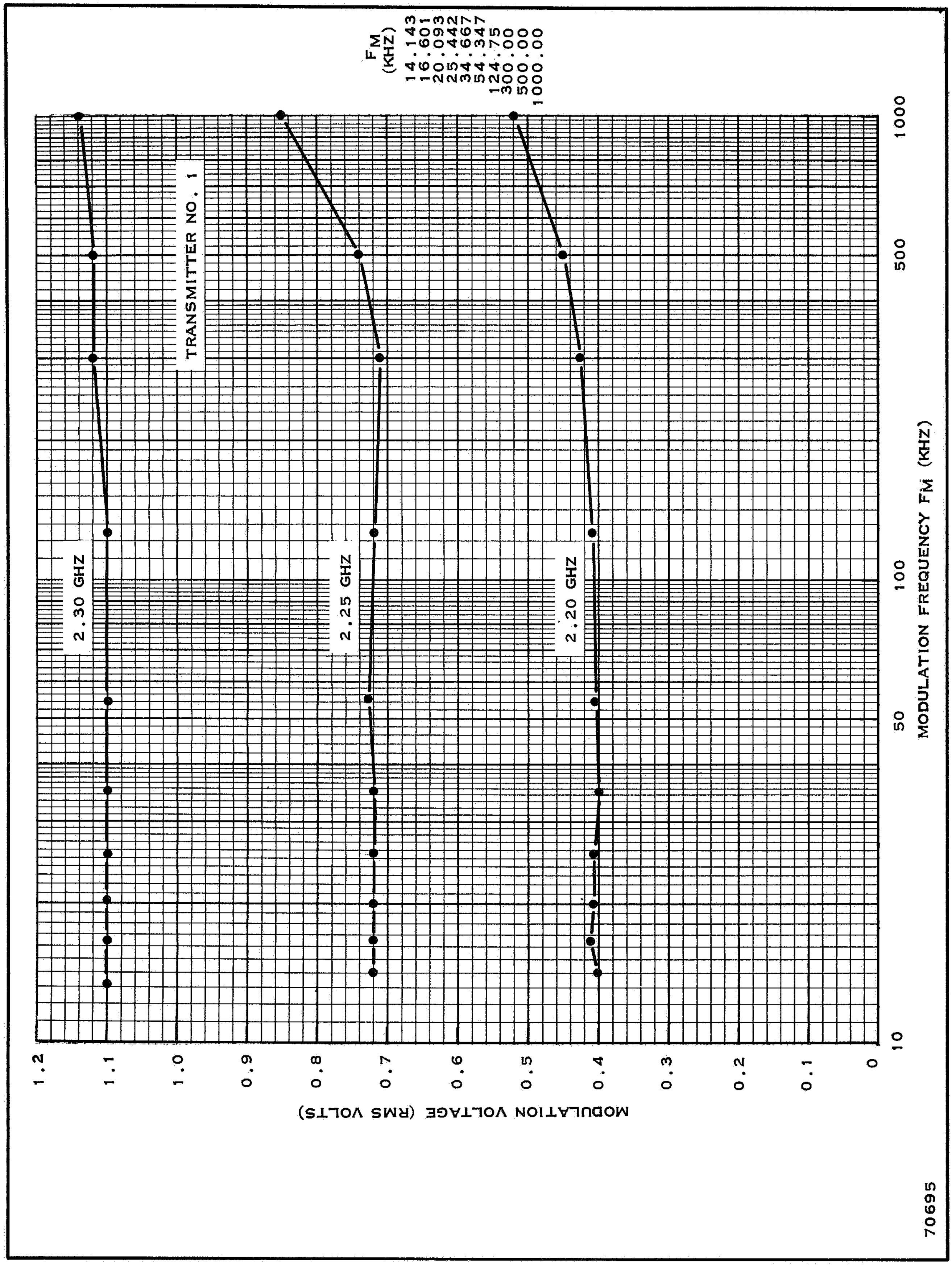


Figure 22. Transmitter No. 1—Modulator Frequency Response

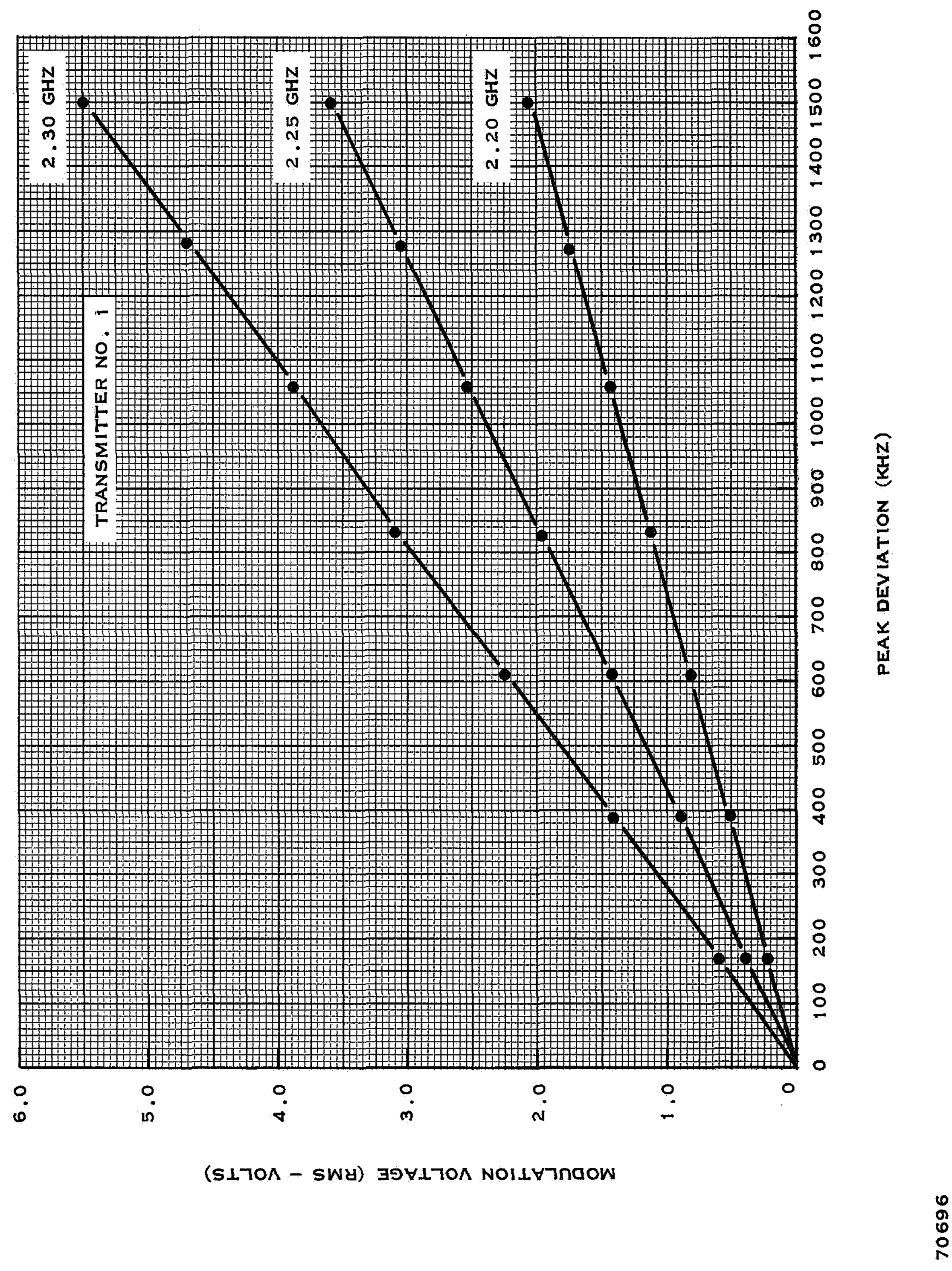


Figure 23. Transmitter No. 1–Deviation Versus Modulation Voltage

where $V_{(5)}$ = 4.1 volts

$V_{(8)}$ = 7.5 volts

Z_{in} = 725 ohms

g. Spurious Emissions

The transmitter output spectrum was displayed on a spectrum analyzer and all outputs other than the desired frequency were measured relative to the desired signal.

Frequency (GHz)	**Level Relative to f_0 = 2.25 GHz**
4.5	–37 dB
6.75	–52 dB
9.0	–38 dB

2. *Transmitter No. 2*

a. Size and Weight

2.2 X 1.1 X 0.3 inches

1.3 ounces

b. Center Frequency Stability

Starting Frequency: 2.24994

Frequency after 30 minutes: 2.24916

Δf: 780 kHz

Percentage = 0.035 percent

c. Power Output Versus Frequency

Frequency (GHz)	**Output Power (mW)**	**Varactor Voltage (volts)**	**I_{total} (mA)**	**Supply Voltage (volts)**
2.10	380	5.8	752	–24.5
2.11	440	6.4	256	–24.5
2.12	550	6.8	258	–24.5
2.13	560	7.4	260	–24.5
2.14	600	7.8	260	–24.5
2.15	630	8.3	260	–24.5
2.16	660	8.8	260	–24.5
2.17	680	9.2	258	–24.5
2.18	680	9.7	256	–24.5
2.19	680	10.1	255	–24.5
2.20	680	10.4	255	–24.5

Frequency (GHz)	Output Power (mW)	Varactor Voltage (volts)	I_{total} (mA)	Supply Voltage (volts)
2.21	690	10.8	256	–24.5
2.22	730	11.2	258	–24.5
2.23	760	11.7	260	–24.5
2.24	790	12.3	261	–24.5
2.25	790	12.9	260	–24.5
2.26	780	13.5	257	–24.5
2.27	760	14.3	255	–24.5
2.28	740	15.0	252	–24.5
2.29	710	15.6	249	–24.5
2.30	680	16.6	246	–24.5
2.31	650	17.8	243	–24.5
2.32	610	19.2	240	–24.5
2.33	560	21.0	235	–24.5

A plot of the output power versus frequency is shown in Figure 24.

d. Efficiency

2.20 GHz–10.9 percent

2.25 GHz–12.4 percent

2.30 GHz–11.3 percent

e. Modulation Characteristics

(1) Modulation Frequency Response

f_m (kHz)	f_0 = 2.20 GHz (V_m)	f_0 = 2.25 GHz (V_m)	f_0 = 2.30 GHz (V_m)	Deviation (kHz)
14.143	0.34	0.57	1.0	300
16.601	0.34	0.57	1.0	300
20.093	0.34	0.59	0.99	300
25.442	0.34	0.57	0.99	300
34.667	0.34	0.57	1.0	300
54.347	0.34	0.57	1.0	300
124.750	0.34	0.57	1.02	300
300.000	0.35	0.61	1.04	300
500.000	0.36	0.61	1.06	300
1000.000	0.44	0.70	1.2	300

A plot of the modulation frequency response is shown in Figure 25.

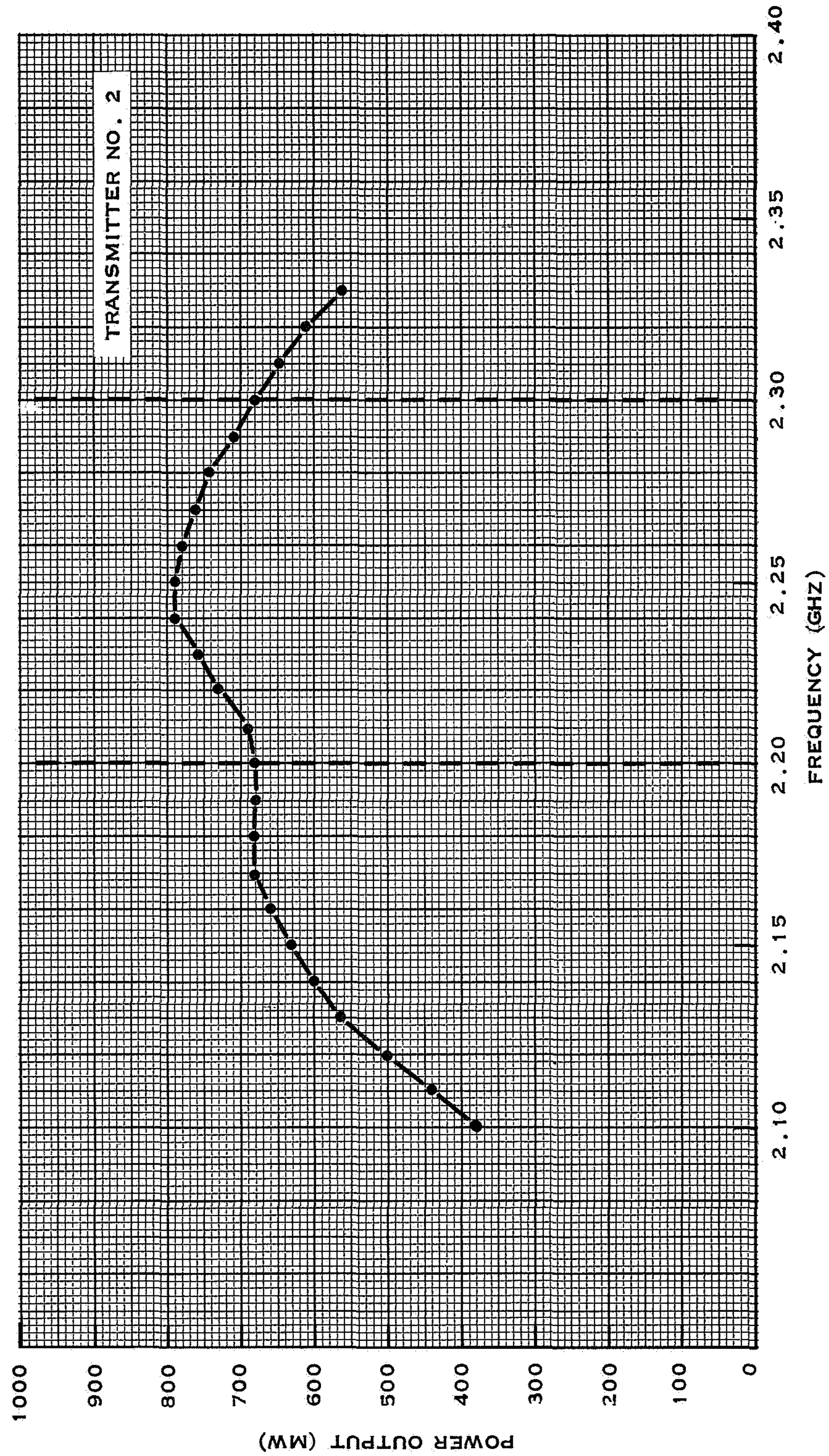


Figure 24. Transmitter No. 2—Power Output Versus Frequency

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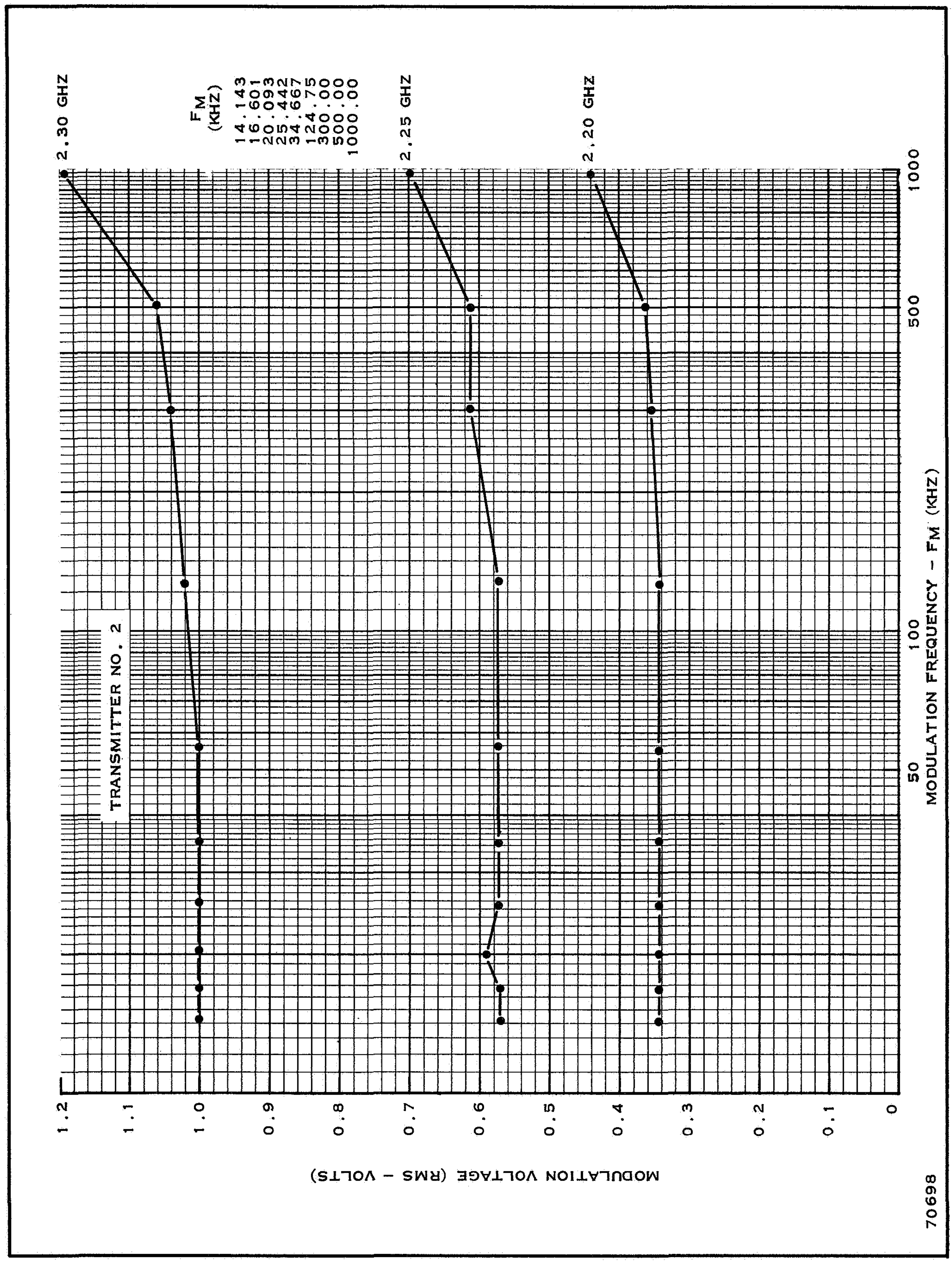

Figure 25. Transmitter No. 2—Modulation Frequency Response

(2) Deviation Linearity

Peak Deviation (kHz)	Carrier (zero)	f_0 = 2.20 GHz V_m (volts)	f_0 = 2.25 GHz V_m (volts)	f_0 = 2.30 GHz V_m (volts)
170.057	1	0.196	0.33	0.56
340.359	2	0.45	0.77	1.3
611.955	3	0.61	1.20	2.05
833.847	4	0.97	1.65	2.80
1055.853	5	1.22	2.06	3.51
1277.915	6	1.47	2.55	4.3
1500.000	7	1.74	2.95	5.1

A plot of the deviation versus modulation voltage is shown in Figure 26.

(3) Deviation Sensitivity

Using the 2.25-GHz curve in Figure 26, the deviation sensitivity is 0.193 volt per 100 kHz.

f. Input Impedance

$$Z_{in} = \frac{V_{(5)} \times 600}{V_{(8)} - V_{(5)}}$$

where

$V_{(5)}$ = 3.00 volts

$V_{(8)}$ = 5.3 volts

Z_{in} = 780 ohms

g. Spurious Emissions

Frequency (GHz)	Level Relative to f_0 = 2.25 GHz
4.5	-32 dB
6.75	–31 dB
9.0	–46 dB

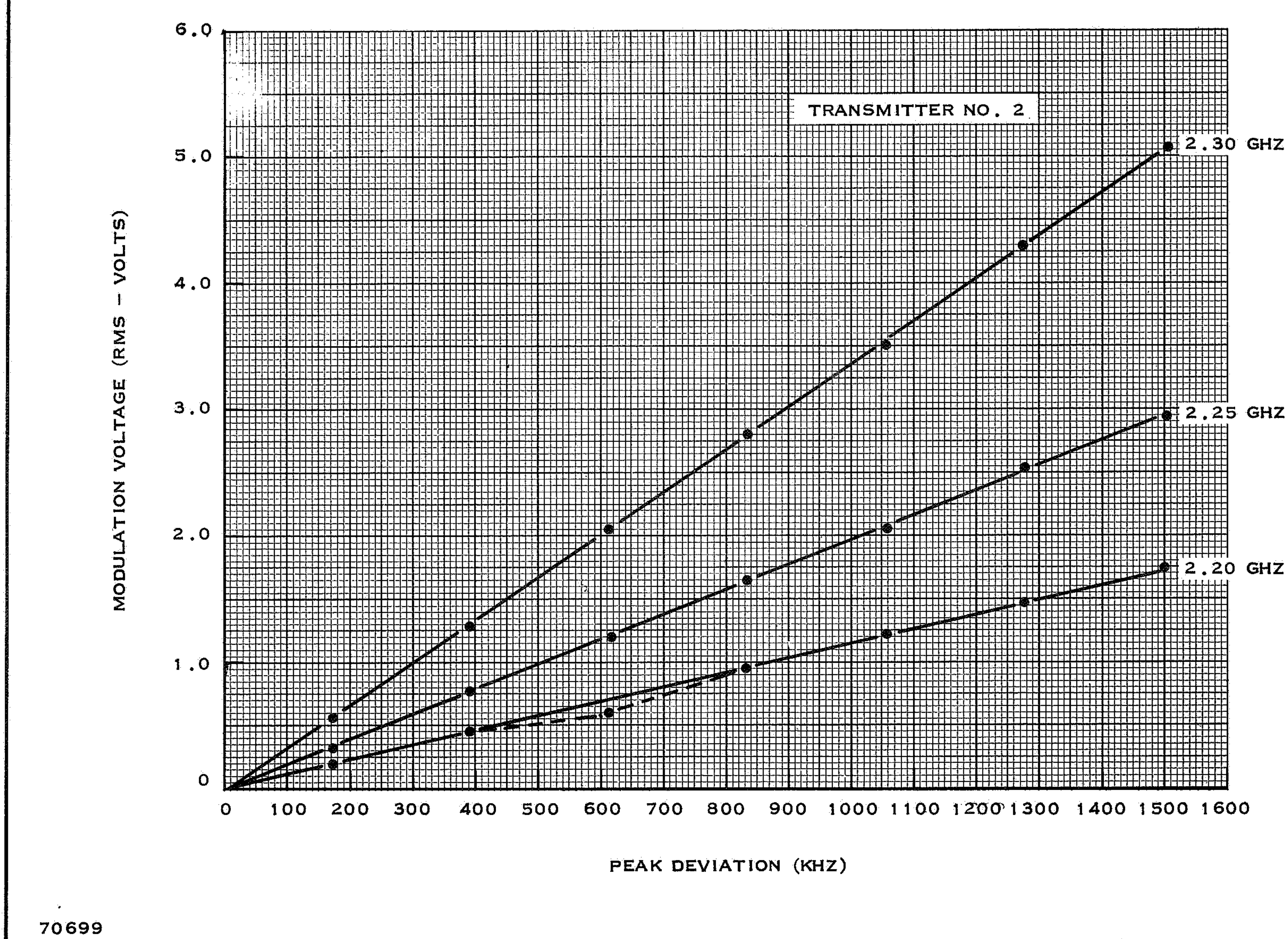

Figure 26. Transmitter No. 2–Deviation Versus Modulation Voltage

SECTION V

CONCLUSIONS

With the successful fabrication and test of the two transmitters and two receivers, the use of integrated circuits at microwave frequencies was clearly demonstrated.

As new and higher power devices become available, it will be possible to increase the transmitter output power to several watts with a relatively small increase in size, thus making the use of microwave integrated circuits very desirable for space telemetry applications.

The low noise image terminated balanced mixer demonstrated that receivers with good noise figures at microwave frequencies are indeed practical and feasible. The lightweight and smallness of size also demonstrated the desirability of integrated circuits for applications involving space communications.

SECTION VI

PROGRAM PERSONNEL

James C. Pinac . . . . Project Engineer

Wayne J. Harrison . . . . Technician

Paul Cleveland . . . . Technician